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PERIGLACIAL INVOLUTIONS IN NORTH-EASTERN ILLINOIS

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ABSTRACT

Certain beds of glaciofluvial sand, silt, and clay in the upper Illinois Valley are complexly deformed into variously shaped masses of silt and clay intruded into sand. Rounded forms and downward intrusions predominate. Individual structures are termed "involutions," and layers of deformed beds are called "involution layers"—equivalents of the *Brodelböden* and *Brodelzonen* of German writers. Deformation has not been observed below a depth of 12 feet and may extend within 3 or 4 feet of the surface. Single involution layers are from a few inches to 6 feet thick.

These involutions are attributed to intense differential freezing and thawing and to the development and melting of masses of ground ice. It is postulated that this occurred in a surficial layer above perennially frozen ground in an area peripheral to a glacier where periglacial (arctic) conditions prevailed. The involutions are believed to have been formed when the ice front lay 30–50 miles to the northeast and are dated as late Cary (late Middle Wisconsin).

INTRODUCTION

INTRODUCTORY STATEMENT

This article deals with only one of a large number of phenomena attributed to processes active under the arctic conditions prevailing in certain areas during the Pleistocene. Similar structures have been described from Europe, and the references cited in the following pages indicate the great amount of foreign work on this and closely related subjects. The features to be described were first observed in 1938 and have been studied at various intervals since.

HISTORICAL SUMMARY

Soil structures produced by frost action were recognized by Lovén in Spitzbergen in 1837.[1] Publications by Högbom,[2] K. Sapper,[3] and Axel Hamberg[4] and the 11th International Geological Congress expedition to Spitzbergen in 1910 subsequently aroused great interest in the work of frost at high latitudes and in high altitudes. As early as 1866 Rev. O. Fisher[5] suggested that certain features in England were "fossil" forms produced by frost action in Pleistocene-glacial or early postglacial time. Work on this subject became exceptionally vigorous after 1925 with the appearance of a great mass of German literature devoted to features in central Europe produced by frost action during the Pleistocene glaciation. This notable increase in periglacial studies was undoubtedly inspired partly by Paul Kessler's book[6]—a stimulating review of earlier work and an excellent compilation of periglacial concepts. Kirk Bryan[7] has been chiefly responsible for introduction of the periglacial concept into this country, and papers by him and by Ernst Antevs[8] have inspired other American studies.[9]

[1] Bertil Högbom, "Über die geologische Bedeutung des Frostes," *Bull. Geol. Inst. Univ. Upsala*, Vol. XII (1914), p. 309.

[2] *Ibid.*, pp. 257–398; "Beobachtungen aus Nordschweden über den Frost als geologischer Faktor," *ibid.*, Vol. XX (1926), pp. 243–79.

[3] "Erdfliessen und Strukturboden in polaren und subpolaren Gebieten," *Internat. Mitt. f. Bodenkunde* (1914).

[4] "Zur Kenntnis der Vorgänge im Erdboden beim Gefrieren und Auftauen sowie Bemerkungen über die erste Kristallization des Eises in Wasser," *Geol. Foren. i Stockholm Forhandl.*, Vol. XXXVII (1915), pp. 583–619.

[5] "On the Warp (of Mr. Trimmer)—Its Age and Probable Connexion with the Last Geological Events," *Quart. Jour. Geol. Soc. London*, Vol. XXII (1866), pp. 563–64.

[6] *Das eiszeitliche Klima, und seine geologischen Wirkungen im nicht vereisten Gebiet* (Stuttgart, 1925), pp. 1–210.

[7] "Glacial Climate in Non-glaciated Regions," *Amer. Jour. Sci.*, Vol. XVI (1928), pp. 162–64.

[8] *Alpine Zone of Mt. Washington Range* (Auburn, Me., 1932), pp. 1–118.

[9] C. S. Denny, "Periglacial Phenomena in Southern Connecticut," *Amer. Jour. Sci.*, Vol. XXXII (1936), pp. 322–42; "Glacial Geology of the Black Rock Forest," *Black Rock Forest, Bull. 8* (1938), pp. 1–70; "Stone-Rings on New Hampshire Mountains," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 432–38; H. T. U. Smith, "Periglacial Landslide Topography of Canjilon Divide, Rio Arriba County, New Mexico," *Jour. Geol.*, Vol. XLIV (1936), pp. 836–60; W. E. Powers, "The Evidence of Wind Abrasion," *Jour. Geol.*, Vol. XLIV (1936), pp. 214–19; R. P. Goldthwait, "Geology of the Presidential Range," *N.H. Acad. Sci. Bull. 1* (1940), pp. 37–39.

TERMINOLOGY

W. Lozinski[10] appears to have been one of the first to use the term "periglacial," although neither he nor anyone else seems to have defined it. A periglacial environment is characterized by low temperatures, strong winds, and many fluctuations across the freezing-point at certain seasons. Various features resulting from processes promoted by such an environment are termed "periglacial." Unfortunately, this designation has been rather loosely used both for "fossil" and modern features and for ones not necessarily formed in an area peripheral to a glacier. The structures described herein are periglacial in the strictest sense, having been formed under the arctic conditions of an area peripheral to a glacier.

A term widely used in foreign circles for these features is *Brodelböden*, introduced by Karl Gripp[11] and subsequently used by others. There is no good English equivalent for *Brodelböden*, and its use is not advisable here because it is a foreign term and, furthermore, carries a certain implication of origin not subscribed to in this article. Bryan[12] suggests "involution" as a suitable term for the aimless deformation, distribution, and interpenetration of beds produced by frost action, and this is the terminology adopted.[13] According to Webster's *New International Dictionary*, an involution is something which is infolded, involved, intricate, or complicated. The structures within the deformed layer may be spoken of as "involutions," and any single structural unit separable from its associated forms may be termed an "involution." The deformed layer or zone is the "involution layer."

PHYSICAL RELATIONS

LOCATION

Involutions are exposed in the banks of a large strip coal mine, Pit 6 of the Northern Illinois Coal Corporation, $2\frac{1}{2}$ miles northeast

[10] "Über die mechanische Verwitterung der Sandsteine im gemässigten Klima," *Acad. sci. Cracovie, Cl. sc. math. et naturw. Bull. I.S* (1909); "Die periglaziale Fazies der mechanischen Verwitterung," *12th Internat. Geol. Cong., C. R.* (1910), p. 1039.

[11] "Beiträge zur Geologie von Spitzbergen," *Abh. naturw. Verein Hamburg*, Vol. XXI (1927). Pp. 38.

[12] Personal communication.

[13] See also Denny, "Periglacial Phenomena . . . .," *op. cit.*, p. 338; Kirk Bryan and L. L. Ray, "Geologic Antiquity of the Lindenmeier Site in Colorado," *Smithsonian Misc. Coll.*, Vol. XCIX (1940), p. 26.

of Coal City, Grundy County, northeastern Illinois (Fig. 1). This region is in the Morris Basin of the upper Illinois Valley, and the pit is at the eastern edge of the Morris quadrangle in Secs. 24 and 25, T. 33 N., R. 8 E. Constant opening of new exposures has afforded exceptionally favorable opportunity for successive observations.

The area between Coal City and the junction of the Kankakee and Des Plaines rivers to the north (Fig. 1) consists of a group of terrace-like flats separated by low, northward-facing escarpments, presumably ancient shorelines or river banks. Two of these escarpments appear just northeast of Coal City, the first at an elevation of 560 feet—the Lake Morris shoreline—and the second at the 540-foot contour—the Cryder Lake shoreline.[14] The coal pit has been dug into the flat about midway between these shorelines at an elevation close to 550 feet.

GEOLOGICAL SETTING

Geological relations at the coal pit are illustrated in Figures 1 and 2. A representative section consists of bedrock, a few feet of till, 10–30 feet of water-laid material, 2–3 feet of weathered sand and illuvial clay, and $1\frac{1}{2}$–3 feet of loamy soil.

The till is unweathered and blue-gray in color except near the north end of the pit where it contains considerable pink material. Its freshness indicates a probable Wisconsin age, and the location of the pit inside the Marseilles moraine and outside the Minooka (Fig. 1) suggests that at least some of the blue-gray till is Marseilles, although the pink material resembles Bloomington till. The water-laid deposits above contain the involutions and are moderately well-sorted, horizontal beds consisting of 85–95 per cent sand and 5–15 per cent clay, silt, and gravel. The gravels, except for a basal bed, are thin, discontinuous lenses containing roundstones of limestone, chert, and various crystalline rocks. The sand is chiefly clean, well-sorted, fine- to medium-sized quartz grains and locally contains small fragments of coal, armored clay pellets, and sparse roundstones up to 8 inches in diameter. The finer materials consist of sizes between clay and very fine sand and appear in thin interbedded layers that may be locally abundant but have no great lateral ex-

[14] H. E. Culver, "Geology and Mineral Resources of the Morris Quadrangle, Illinois," *Ill. State Geol. Surv. Bull. 43* (1923), pp. 180–81.

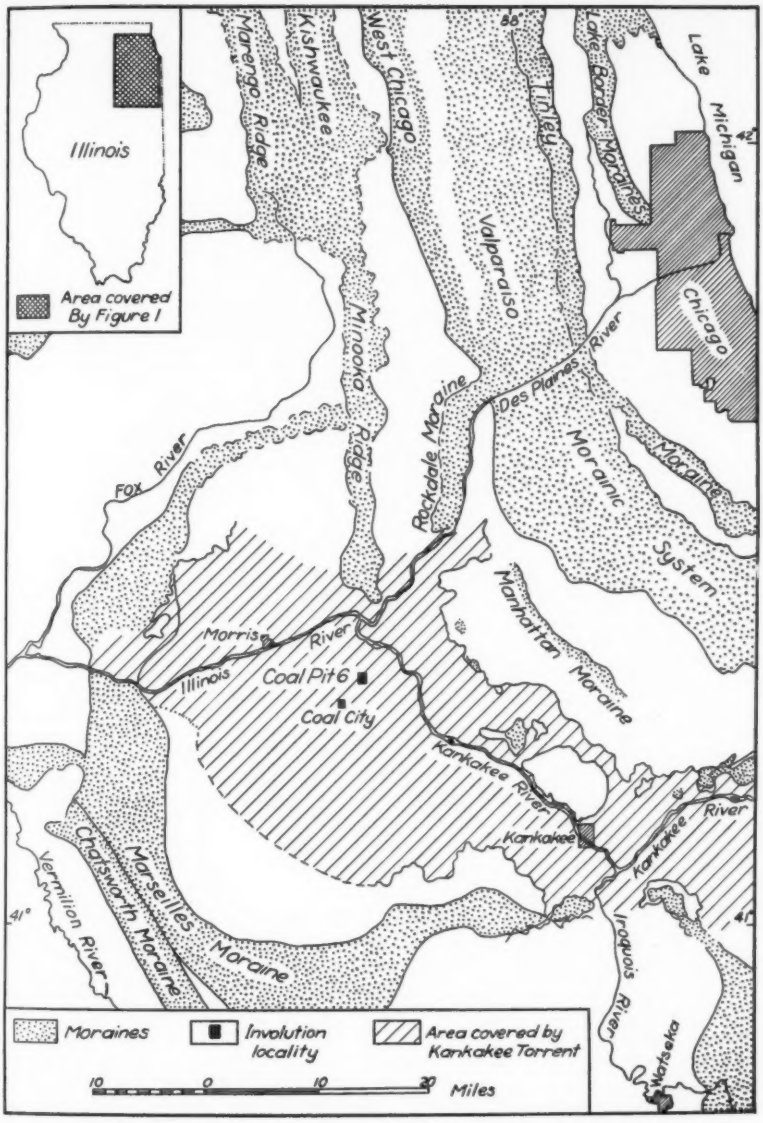

FIG. 1.—Map of involution locality, moraines, and area covered by Kankakee torrent. Based upon published works and subject to alteration by Illinois Geological Survey reports in preparation or in press.

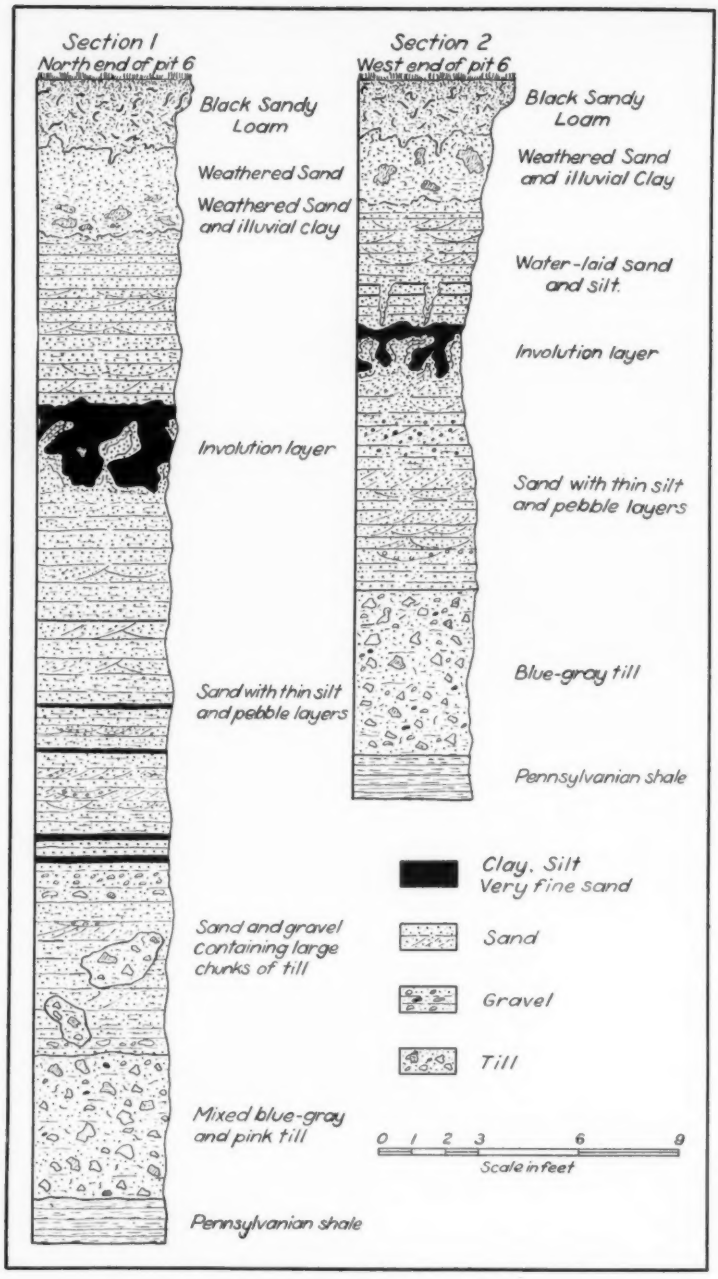

FIG. 2.—Representative sections of Pleistocene deposits at Pit 6

tent. Scour channels, cross-bedding, and foreset beds occur in nearly every exposure. The water-laid materials are probably Kankakee torrent deposits[15] of late- or slightly post-Valparaiso age (late Middle Wisconsin). They grade upward into a layer of structureless brown weathered sand which contains considerable illuvial clay, particularly toward the bottom where the clay has accumulated in irregularly distributed masses. The soil layer at the top consists of a black,

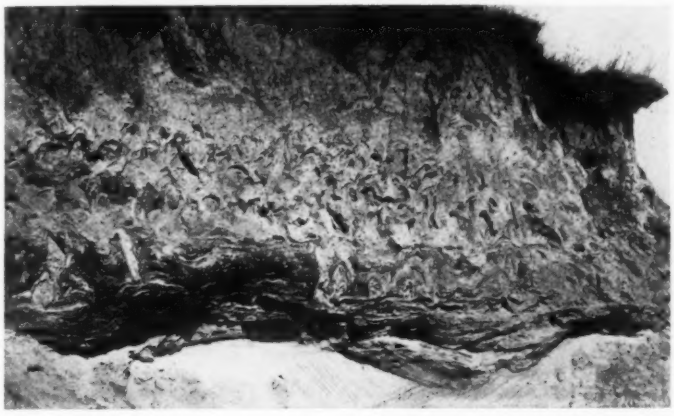

FIG. 3.—Involution layer in central part of Pit 6. Aimless interpenetration of sand and silt masses shown. Sand weathers out, leaving silt masses projecting. Maximum depth of deformation is 10 feet.

carbonaceous sandy loam containing irregularly distributed masses of clay and a maze of small plant roots. Toward the bottom it is moderately rich in illuvial clay, and the contact with the underlying sand is transitional and irregular.

INVOLUTIONS

DESCRIPTION

The involutions consist largely of intensely deformed, involved, and haphazardly interpenetrating masses of silt and sand originally arranged in horizontal beds. Masses of silt have been intruded into

[15] G. E. Ekblaw and L. F. Athy, "Glacial Kankakee Torrent in Northeastern Illinois," *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), pp. 417–28.

the sand, which has thereby been considerably disturbed. Most abundant are the teardrop-, tenpin-, jug-, and boot-shaped masses (Figs. 4 and 5) of silt irregularly connected by thin stringers and tongues extending through the sand. Rounded or curved outlines predominate, but sharp, angular forms are not entirely lacking. Seemingly isolated nests of sand or lumps of silt are usually connected with other sand or silt masses in the third dimension. Some

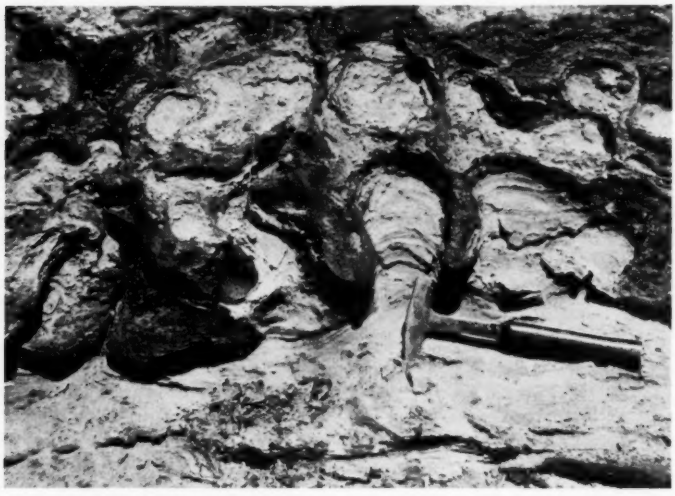

FIG. 4.—Involutions at north end of Pit 6. Dark material is silt; light material is sand. Note deformation of sand near hammer. Exposure on vertical face at depth of 12 feet.

of the structures appear to be ordinary folds, irregularly compressed and associated with intrusive masses like those just described; however, these folds are sparse, discontinuous, and of limited axial extent. In general there is a notable similarity and uniformity in separate involution layers, but they vary considerably in detail.

A highly distinctive feature of the involutions is their lack of linear trend or continuity. Sections cut at right angles in the same involution layer differ only in the minor details of size, shape, and arrangement of the silt and sand masses (Fig. 6). As a vertical section

through an involution layer is cut back parallel to itself, the size, shape, and arrangement of the intrusions change constantly (cf.

FIG. 5.—Boot-shaped intrusion of silt in sand. Lack of corresponding deformation in overlying beds indicates plasticity and migration of silt.

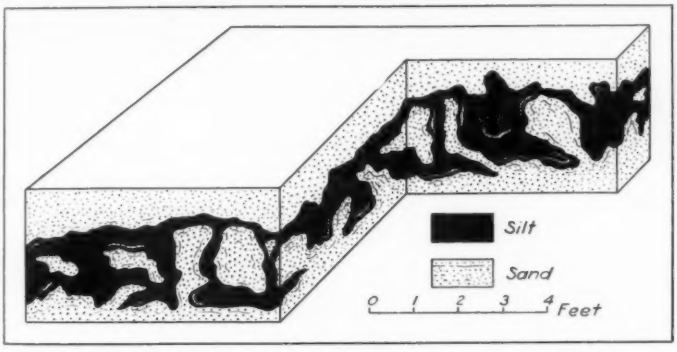

FIG. 6.—Right-angle sections in involution layer. Sketched from artificial cut made in field. Lack of linear trends or continuity of structures notable.

Figs. 7 and 8). Even seemingly ordinary folds have little axial extent and are replaced by other wholly unrelated structures. There is no evidence of the linear trend expected in structures resulting from

normal compressional deformation. Furthermore, deformation appears only in places where sand and silt are interbedded, being absent where the section consists entirely of sand.

K. Keilhack[16] has likened involutions (*Brodelböden*) to the structures produced by thrusting a blunt stick at various points into horizontally bedded plastic materials so that one bed is thrust and kneaded into another. The impression that lumps of silt have been thrust upward or downward into adjoining beds is gained from close observation of vertical sections and has been recognized by Adolf

FIG. 7.—Vertical cut in involution layer. Compare with Figure 8

Bahr[17] in his terms *Sinkmassen* and *Steigmassen*. Since horizontal or inclined sections through involution layers show somewhat similar relations, it seems likely that intrusion has occurred in all directions and not simply upward or downward. In many exposures, however, downward intrusions do predominate. Because a simple downward or upward punching of a bed is not enough to account for the size of the silt masses, considerable lateral migration of silt to form the in-

[16] "Über Brodelböden im Taldiluvium bei Senftenberg und über das Alter der sie begleitenden Torf- und Faulschlammablagerungen," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXXIX, Monatsber. B. (1927), p. 364; "Die geologischen Verhältnisse in der Niederlausitz, mit besonderer Berücksichtigung der alten und neuen Tagebau der Ilse Bergbau-Actiengesellschaft," (privately printed, 1938), pp. 84–85.

[17] "Frostgestauchte Böden im westlichen Schleswig-Holstein," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXXXIV (1932), p. 24.

trusions is indicated. This movement of material to centers of intrusion would account for the marked pinching and swelling of the silt beds and would help explain the relatively slight deformation of beds immediately overlying some downthrust intrusions (Fig. 5). The intense deformation in most layers also terminates downward rather abruptly, so that the underlying beds are undisturbed.

Irregularities in the soil zones consist chiefly of localized accumulations of illuvial clay and tubular or odd-shaped bodies of loam. The general appearance of these irregularities is not that of an in-

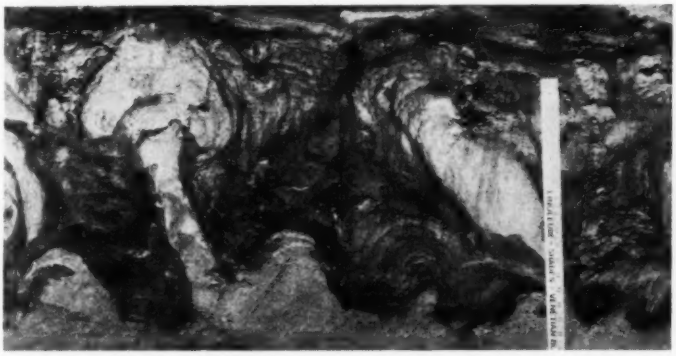

FIG. 8.—Face of same bank shown in Figure 7 cut back about 1 foot. Note changes in size, shape, and distribution of sand and silt masses.

volution layer, although possibly some of them may be remnants of a weathered involuted layer in which the secondary changes have largely obscured the earlier relations. For the most part, however, they are attributed to modern processes of weathering, minor frost heaving, and the action of organisms.

NATURE OF INVOLUTED MATERIALS

The Morris Basin involutions are limited to exposures containing at least some beds of silt or clay and are lacking in sections consisting wholly of sand. A channel sample taken from the core to the sandy rim of a silty intrusive mass consists of the following sizes of material (Wentworth grade scale) in the following percentages: 0.5 granule, 0.4 very coarse sand, 1.5 coarse sand, 12.8 medium sand, 23.7 fine

sand, 26 very fine sand, 31.3 silt (13 coarse silt, 9.5 medium silt, 6.7 fine silt, 2.1 very fine silt), and 4 clay. A sample of another silt intrusive taken from the core only contains 39.8 per cent fine and very fine sand, 49.2 silt (12.8 coarse silt, 18.3 medium silt, 12.4 fine silt, 5.7 very fine silt), and 11.4 clay. Elsewhere in the pit thin beds of the following constitution have been deformed: 2 per cent very fine sand, 32.1 silt (1.4 coarse silt, 18.5 medium silt, 12.2 fine and very fine silt), and 66 clay.

The predominance of fine and very fine sand and the various grades of silt is characteristic. The third analysis shows that at least some beds containing a large amount of clay may be deformed. The sand beds incorporated in the involutions consist of medium, fine, and very fine sand in various proportions. Pebbles up to $\frac{1}{4}$ inch in diameter have been found in the deformed material, but they are usually few and scattered, although at one place a $\frac{1}{2}$-inch pebble layer was involved. In other areas involutions have been reported in gravels,[18] and gravel beds adjacent to an involuted silt lens near Watseka, Illinois,[19] have also been deformed.

INVOLUTION LAYERS

INVOLUTION LAYERS IN PIT 6

The involution layers in Pit 6 are from a few inches to 6 feet thick (Fig. 3), with an average at 2–3 feet, and in many cases have rather sharp upper and lower boundaries. The deepest involutions are 12 feet below the surface (Fig. 2, sec. 1), and most are 5–10 feet deep, although some extend to within 3 or 4 feet of the surface, where they merge with and are obscured by the lower soil zones (Fig. 3). The thickness and distribution of the deformed layers are controlled primarily by the constitution of the beds, except that beds of favorable composition below a depth of 12 feet are not deformed. Usually only one involution layer is seen in a single exposure, but in a few

[18] F. Krekeler, "Fossile Strukturböden aus der Umgebung von Giessen und Wiesbaden," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXXXI (1929), pp. 460–61; Bahr, "Frostgestauchte Böden . . . . ," *op. cit.;* Bryan and Ray, "Geologic Antiquity . . . . ," *op. cit.*, p. 26.

[19] This locality is in a gravel pit 4½ miles northeast of Watseka on the banks of the Iroquois River (SW. ¼ Sec. 30, T. 27 N., R. 11 W.). It was called to the writer's attention in 1939 by Dr. G. E. Ekblaw of the Illinois State Geological Survey.

places where two or more groups of suitable beds exist two or more involution layers, separated by seemingly undeformed materials, have been observed. There is no indication that these separate layers were deformed at different times, although two or more involution layers of different ages in single exposures have been described from widely separated parts of Europe.[20]

INVOLUTION LAYERS IN OTHER LOCALITIES

Involution layers showing features which are almost the exact replica of those in Pit 6 have been pictured and described from many places in Europe.[21] Joshua Trimmer and Fisher,[22] Denny,[23] and Bryan and Ray[24] have described involutions from England, Connecticut, and Colorado, respectively.

Involutions have also been observed in Pit 7 of the Northern Illinois Coal Corporation, 3 miles northwest of Pit 6, and in a gravel pit $4\frac{1}{2}$ miles northeast of Watseka, Illinois. The involutions at Watseka were discovered by Dr. G. E. Ekblaw. Leland Horberg has observed an older well-developed involution layer near Cambridge in Henry County, western Illinois, and near Davenport, Iowa. J. H.

[20] Ernst Becksmann, "Fossile Brodelböden im Profile des Roten Kliffs (Sylt) und damit zusammenhängende diluvialgeologische Fragen, *Neues Jahrb. f. Min., Geol., u. Paläo.*, Beilage LXVI, Abt. B (1931), pp. 440, 453, 456, 460–61; H. Breuil, "De l'importance de la solifluxion dans l'étude des terrains quaternaires du nord de la France et des pays voisins," *Rev. géog. phys. et géol. dynamique*, Vol. VII (1934), pp. 269–332; Keilhack, "Über Brodelböden im Taldiluvium . . . . ," *op. cit.*, pp. 364–65; "Die geologischen Verhältnisse in der Niederlausitz . . . . ," *op. cit.*, pp. 86–88.

[21] E. Horn, "Die geologischen Aufschlüsse des Stadtparkes in Winterhude und des Elbtunnels und ihre Bedeutung für die Geschichte der hamburger Gegend in postglazialer Zeit," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXIV (1912), pp. 133–34; W. Wolff, "Einige glazialgeologische Probleme aus dem norddeutschen Tiefland," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXXIX, Monatsber. B. (1927), pp. 344–45; Alfred Dücker, "Steinsohle oder Brodelpflaster," *Centralbl. f. Min., Geol., und Paläo.*, Abt. B (1933), pp. 265–66; Otto Wittmann, "Diluvialprofile mit periglazialen Erscheinungen im Donaugebiet bei Immendingen," *Jahresber. u. Mitt. der Oberrheinischen geol. Vereins*, Vol. XXV (1936), pp. 99–101, 105.

[22] Trimmer, "Generalizations Respecting the Erratic Tertiaries or Northern Drift," *Quart. Jour. Geol. Soc. London*, Vol. VII (1851), pp. 19–31; Fisher, "On the Warp (of Mr. Trimmer) . . . . ," *op. cit.*

[23] "Periglacial Phenomena . . . . ," *op. cit.*

[24] "Geologic Antiquity . . . . ," *op. cit.*, pp. 26, 61.

Lees[25] pictures and describes a deformed layer in glacial deposits in Iowa which looks like a typical involution layer, although he attributes the deformation to slumping.

ORIGIN OF INVOLUTIONS

GENERAL STATEMENT

The following agents and processes might be considered as possible participants in the formation of involutions: (1) organisms, both plants and animals;[26] (2) earthquakes; (3) springs;[27] (4) pressed melt;[28] (5) mass movements;[29] (6) convection currents; (7) ice shove; (8) differential loading; (9) repeated differential freezing and thawing and development of masses of ground ice. The particular physical and geological relations at the coal pit appear to eliminate the first five items from further consideration, although it must be admitted that at least some of them can cause involution-like deformation under proper conditions.

CAUSES OF DEFORMATION

Convection currents.—A. R. Low[30] has suggested that soil structures in Spitzbergen and elsewhere may have been formed by convection currents set up by the difference in density of water at 0° and 4° C. Gripp[31] has adopted this explanation with some enlargements and modifications, and the feasibility of the Low-Gripp hypothesis has been the subject of an extended discussion in the foreign literature.[32]

[25] "Geology of Crawford County, Iowa," *Iowa State Geol. Surv. Ann. Rept. 1925–26*, Vol. XXXII (1927), p. 335.

[26] H. J. Lutz and F. S. Griswold, "The Influence of Tree Roots on Soil Morphology," *Amer. Jour. Sci.*, Vol. CCXXVII (1939), pp. 389–400.

[27] H. Behlen, "Eine neue Theorie der Struktur-(Steinring-, Steinnetz-, oder Brodel-) Böden," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXXXII (1930), pp. 635–36.

[28] R. G. Carruthers, "On Northern Glacial Drifts: Some Peculiarities and Their Significance," *Quart. Jour. Geol. Soc. London*, Vol. XCV (1939), pp. 299–330.

[29] W. J. Miller, "Intraformational Corrugated Rocks," *Jour. Geol.*, Vol. XXX (1922), pp. 587–610.

[30] "Instability of Viscous Fluid Motion," *Nature*, Vol. CXV (1925), pp. 299–300.

[31] "Beiträge zur Geologie von Spitzbergen," *op. cit.*

[32] C. S. Elton, "The Nature and Origin of Soil-Polygons in Spitzbergen," *Quart. Jour. Geol. Soc. London*, Vol. LXXXIII (1927), pp. 172–73, 183–84; Hans Mortensen, "Über die physikalische Möglichkeit der 'Brodel'—Hypothese," *Centralbl. f. Min., Geol., u. Paläo.*, Abt. B (1932), pp. 417–22; Alfred Dücker, "Frostschub und Frosthe-

This theory does not seem applicable here, for it is difficult to attribute the intrusions in the involution layers to convection currents set up by the slight density difference of water at 0° and 4° C. In addition the involutions do not have the rather simple cell-like structure required by this theory.

Differential loading.—If clay or silt interbedded with sand and saturated with water were subjected to a differential overburden, the interpenetration of these materials might occur, thus producing involution-like structures.[33] The present overburden at the coal pit is notably uniform and not particularly heavy. Where the involutions extend close to the surface there is practically no superadjacent load. Three possible sources of pre-existing differential overburden may be considered briefly: (1) sand dunes, (2) overlying glacial or glaciofluvial deposits now removed, and (3) glacial ice. Low fixed dunes lie along the northern edge of the flat into which the coal pit is dug. They are built of sand from a shore or beach just to the north and have always been fixed at essentially their present position. They did not move across that part of the flat in which the involutions are exposed. There is no independent evidence of a former overburden of glacial or glaciofluvial deposits in this area, and the probability that the deformed beds are Kankakee torrent materials largely eliminates the possibility of such an overburden. An overburden of glacial ice is in somewhat the same category, for the ice had retreated nearly into the Lake Michigan basin by the time the Kankakee torrent deposits were formed, and it never re-entered the area. If differential overburden were the right explanation, involutions should be found in nonglacial and nonperiglacial areas. Furthermore, it is questionable that differential overburden could produce the small-scale complexities observed in the involutions.

Ice shove.—Deformation of unconsolidated glaciofluvial materials

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bung," *Centralbl. f. Min., Geol., u. Paläo.*, Abt. B (1933), pp. 441–45; Karl Gripp and W. G. Simon, "Experimente zum Brodelboden-Problem," *Centralbl. f. Min., Geol., u. Paläo.*, Abt. B (1933), pp. 433–40; "Nochmals zum Problem des Brodelbödens," *ibid.* (1934), pp. 283–86; Hans Poser, "Bemerkungen zum Strukturbodenproblem," *Centralbl. f. Min., Geol., u. Paläo.*, Abt. B (1934), pp. 39–45.

[33] E. M. Kindle, "Deformation of Unconsolidated Beds in Nova Scotia and Southern Ontario," *Bull. Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 326–27.

has been commonly attributed to shove by moving ice, either glaciers or bergs and floes, and this appears to be an entirely reasonable explanation in many places. The considerable areal extent of the involutions, their limitation to exposures containing beds of clay or silt, the lack of linear trend even in small details, and the intrusive relations show that they could not have been formed by the shove of floating ice masses or by glaciers. Furthermore, if a glacier occupied the coal-pit area after deposition of the water-laid beds, all evidence of that occupation has been removed, and, granting that the deformed materials are Kankakee torrent deposits, the possibility of a subsequent ice invasion can be eliminated by the known succession of geological events.

Repeated differential freezing and thawing and the formation of ground ice.—These processes acting in a surficial layer above perennially frozen ground are believed competent to produce involutions. Discussion and understanding of this hypothesis is facilitated by the following information.

1. The ground in areas peripheral to the Pleistocene continental glaciers, except for a surficial layer, was probably perennially frozen to a considerable depth as indicated by present areas of frozen ground in Siberia[34] and Alaska.[35] Perennially frozen ground below a surficial thawed zone promotes repeated fluctuations across the freezing-point in the surficial layer during certain seasons and serves to concentrate water there by preventing downward seepage and percolation. The surficial material thus becomes saturated and extremely mobile at times.

2. Annual, seasonal, and daily thawing are limited to a thin surficial layer above perennially frozen ground. Under natural conditions this layer is from only a few feet to 10 or 15 feet thick.

3. Masses of ground ice are formed in areas of perennial ground

[34] G. B. Cressey, "Frozen Ground in Siberia," *Jour. Geol.*, Vol. XLVII (1939), pp. 472–88.

[35] E. de K. Leffingwell, "Ground-Ice Wedges, the Dominant Form of Ground Ice on the North Coast of Alaska," *Jour. Geol.*, Vol. XXIII (1915), pp. 635–37; "The Canning River Region, Northern Alaska," *U.S. Geol. Surv. Prof. Paper 109* (1919), pp. 179–83; P. S. Smith, "Areal Geology of Alaska," *U.S. Geol. Surv. Prof. Paper 192* (1939), pp. 70–71; Ralph Tuck, "Origin of the Muck-Silt Deposits at Fairbanks, Alaska," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 1298, 1309.

frost. The nature and origin of such ice masses have been most completely discussed by Leffingwell[36] and W. Soergel.[37] Many of these ice masses are vertically wedge shaped; but, from the descriptions of the writers cited above, it is clear that nearly as many are lenses, sills, dikes, and various irregular forms. Sizes range from small interstitial granules to masses with dimensions measured in tens of feet. Opinion holds that masses of ground ice form *in situ* under favorable relations of material, water, and temperature and that in most cases they are not buried chunks of glaciers, bergs, or floes.

4. The effect of grain size on repeated freezing and thawing is widely recognized as significant, but its exact role is not completely understood. Inhomogeneities in grain size and texture result in differential freezing and thawing, with the formation of masses of ground ice and concentration of water in certain areas. Notable frost heaving occurs only when masses of ground ice are formed, and it is known that the development of these ice masses is promoted by fine materials.[38] On freezing, clay takes up water from surrounding sandy materials, and repeated freezing and thawing concentrate water in the clay so that it eventually becomes saturated and highly plastic or fluid in the thawed state. Continuation of this process results in a segregation of water from clay to form layers of ice. Curiously enough, soft unfrozen masses of clay can and do exist adjacent to these layers of ice—a condition which may be partly explained by the fact that some of the water in the clay does not freeze readily and can be considerably undercooled. Conflicting statements have been made as to whether coarse or fine material freezes first, and it may be that under different conditions the order of freezing differs.

5. Any theory on the origin of involutions must take cognizance of the structures in the involution layers. The lack of linear trend,

[36] "Ground-Ice Wedges . . . . ," *op. cit.*; "The Canning River Region . . . . ," *op. cit.*, pp. 179–242.

[37] "Diluvial Eiskeile," *Zeitschr. deutsch. geol. Gesellsch.* Vol. LXXXVIII (1936), pp. 223–47.

[38] Stephen Taber, "Frost Heaving," *Jour. Geol.*, Vol. XXXVII (1929), pp. 428–61; "The Mechanics of Frost Heaving," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 303–17. G. Beskow, "Erdfliessen und Strukturböden der Hochgebirge im Licht der Frosthebung," *Geol. Foren. i Stockholm Forhandl.*, Vol. LII (1930), p. 622.

the complex form of the intrusive masses, and the lateral migration of clay and silt indicate that at least part of the material was plastic at the time of deformation and that the deforming forces were uniform neither in direction nor in strength.

Various soil structures have long been recognized as the product of repeated freezing and thawing, but the application of this idea to involutions is more recent. Bahr[39] has given the most complete treatment of the mechanics involved in the formation of involutions (*Brodelböden*) by freezing and thawing. According to him, involutions are formed in the surficial thawed layer above frozen ground at a time when at least part of the materials are in a plastic state. He assumes that the thawed zone refreezes differentially, with the masses of finer material freezing first and acting as centers of pressure from which the forces of expansion radiate, accompanied by changes in direction and strength as freezing progresses and as the various centers unite. The unfrozen and somewhat plastic, mushy material between the centers of freezing is squeezed and intruded into the surrounding beds. It is questionable whether the finer materials freeze first, but this need not invalidate Bahr's concept of pressure centers. Differential freezing and thawing is favored by inhomogeneities such as occur in interbedded sand, silt, and clay layers, and this is one of the reasons why involutions are so well developed in such materials.

Denny[40] has suggested that involutions of Wisconsin age in Connecticut are due to the formation of ground ice, and it is known that the growth of such ice masses does cause deformation.[41] Irregular masses of ground ice would produce structures reflecting their irregularities, and equally important with the structures produced by growth must be the deformation attendant upon melting. The gradual flowage and slumping of thawed material into spaces vacated

[39] "Frostgestauchte Böden im westlich Schleswig-Holstein," *op. cit.*

[40] "Periglacial Phenomena . . . . ," *op. cit.*, p. 338.

[41] Leffingwell, "Ground-Ice Wedges . . . . ," *op. cit.*, pp. 646, 649; "The Canning River Region . . . . ," *op. cit.*, p. 298; Franz Lotze, "Über Schichtaufrichtungen an Klüften," *Zeitschr. deutsch. geol. Gesellsch.*, Vol. LXXXIV (1932), pp. 67–68; T. T. Paterson, "The Effect of Frost Action and Solifluxion around Baffin Bay and in the Cambridge District," *Quart. Jour. Geol. Soc. London*, Vol. XCVI (1940), pp. 100–106.

by melting ground ice would further complicate the forms already produced. Structures which indicate a considerable degree of lateral compression may be more directly the product of expanding ice masses than are the small-scale intrusions.

The existence of frozen ground beneath the deformed layers in the Morris Basin is indicated by the abrupt downward limit of deformation (Fig. 3) and the lack of deformation in suitably constituted beds at greater depths. In several places downward intrusions of silt end abruptly against underlying, undeformed clay or silt beds, and the lateral spreading of the intrusive mass at the contact indicates that it has been pushed with considerable force against an unyielding and hence probably frozen mass. Since surficial thawing presumably penetrated only a few feet, involution layers at a depth greater than 10–15 feet probably have been buried since they were formed.

The evidence of forceful downward intrusion cited above, the lateral movement of silt and clay to form the intrusive masses, and the experimental proof that clay does intrude sand under proper conditions of progressive freezing[42] suggest that the silt and clay masses have been the major active units and that the sand was more or less passively intruded and squeezed into odd shapes by these masses.

SUMMARY STATEMENT OF PREFERRED HYPOTHESIS

The ground in the Morris Basin was perennially frozen to a considerable depth when the Wisconsin glacier lay near by to the northeast. Repeated freezing and thawing in the surficial 5–10 feet produced some structural irregularities in those places where sand and silt or clay were interbedded and led to the development of masses of ground ice. These ice masses grew in times of extended freezing and shrank or disappeared entirely in times of thaw, producing corresponding deformation of the surrounding beds. Once definite irregularities had been introduced, differential freezing and thawing became more effective. Freezing presumably progressed from both above and below, owing to the cooling effect of the frozen ground beneath the surficial thawed layer. However, the predominance of downward intrusions in the involution layers would suggest that freezing from above was dominant. As the top and bottom zones of

[42] Taber, "Frost Heaving," *op. cit.*, p. 455.

freezing approached each other, the layer of partly frozen material between was subjected to considerable stress. Unfrozen plastic material was squeezed between frozen masses and into other unfrozen materials so that various intrusive relations were produced.

A consideration of the Pleistocene history of the upper Illinois Valley and of the climatic conditions in an area close to a continental glacier indicates that all this probably occurred when the ice lay a short distance back from the Valparaiso morainic system, perhaps at either the Tinley or the Lake Border positions or at some intermediate point (Fig. 1). This would place the ice front 30–50 miles northeast of the point where the involutions were being formed and date them as late Cary (late Middle Wisconsin).

SUMMARY

Certain beds of glaciofluvial sand, silt, and clay, presumably deposited by the Kankakee torrent, in the upper Illinois Valley are complexly deformed in a peculiar manner. Variously shaped masses of clay and silt have been intruded into sand. Teardrop-, tenpin-, jug-, and boot-shaped intrusions are common, and rounded outlines and downward intrusions predominate. Lack of linear trend or continuity is a particularly notable feature of these structures. Large-scale migration of clay, silt, and very fine sand to form the intrusive masses indicates considerable plasticity during deformation. The exact replicas of these features have been described from Europe, and similar forms have been observed elsewhere in this country. The structures are termed "involutions," and the layers of deformed beds are called "involution layers"—equivalents of the *Brodelböden* and *Brodelzonen* of German writers. These involutions are developed only where beds of clay or silt are interbedded with sand and are lacking where the section consists wholly of sand. Deformation has not been observed below a depth of 12 feet and may extend within 3 or 4 feet of the surface. Single involution layers are from a few inches to 6 feet thick and usually have rather sharp boundaries, particularly on the under side.

Consideration of a variety of possible modes of origin leads to the conclusion that these involutions are the product of vigorous and repeated differential freezing and thawing and the development

and melting of masses of ground ice. It is postulated that this occurred in a surficial layer above perennially frozen ground in an area peripheral to a glacier where periglacial (arctic) conditions prevailed. Freezing probably occurred both from above and from below owing to the underlying frozen ground, and squeezing of unfrozen plastic material between frozen masses and into other unfrozen material is suggested. All the involutions are thought to be of the same age and are believed to have been formed when the ice front lay 30–50 miles to the northeast. They are dated as late Cary (late Middle Wisconsin).

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THE MALIGNITES OF POOHBAH LAKE, ONTARIO

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ABSTRACT

The Poohbah Lake intrusive is an alkalic stock, some 6 miles long and 2½ miles wide, elongated in a northeast-southwesterly direction. The stock is intrusive into the early pre-Cambrian mica schists in several different facies, among which are malignites and related alkalic types. This is the type locality for malignite. The stock was once described by Lawson, but certain details are added, along with a discussion of its probable origin. Two new chemical analyses are presented. There is no evidence for the presence of a limestone near by, and Bowen's theory of crystallization differentiation best explains the origin of this alkalic stock.

INTRODUCTION

Poohbah Lake is situated in Quetico National Park in western Ontario. Quetico Park lies within the south-central portion of the Quetico map area of the Topographical Survey of Canada. The map area lies between 90° and 92° W. Long. and 48° and 49° N. Lat. The Rainy Lake map area lies immediately to the west.

The Poohbah Lake area is the type locality for the rare malignite and one of the three places where it is known to occur. The two other occurrences are in the Kruger batholith[1] of British Colombia and in the Fen area of Norway.[2] The rocks in the Poohbah area were first described in 1896 by A. C. Lawson.[3] A second reconnaissance survey of the area was made in 1937, but maps[4] are the only results of that investigation which have been published so far. The author spent three weeks in the area in October, 1938, and ten days in October, 1939.

GENERAL GEOLOGY

The consolidated rocks in the area are all pre-Cambrian in age. Drift is fairly abundant throughout the area. The country rock of

[1] R. A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Can. Geol. Surv. Mem. 38* (1912), pp. 448–55.

[2] W. C. Brøgger, *Die Eruptivgesteine des Kristianiagebietes*, Vol. IV: *The Fen Area* (1894).

[3] "Malignite," *Univ. Calif. Pub. Bull. Dept. Geol.*, Vol. I (1896), pp. 337–62.

[4] T. L. Tanton, *Map 534A, Quetico, Canada Dept. of Mines and Resources* (West Half) (1937).

the Poohbah Lake intrusive is a quartz-biotite schist, presumably an altered sediment. The age of these sediments is still in dispute and constitutes the well-known Coutchiching–Knife Lake problem. The schists in the Poohbah area are not in contact with greenstones; consequently, the writer is not in a position to add any evidence on the age of the quartz-biotite schists; and throughout this paper, when quartz-biotite schists are mentioned, reference is to "Coutchiching" or Knife Lake schists.

The Poohbah stock intrudes the quartz-biotite schist. Nothing can be said about the age of the stock, except that it is younger than the country rock. It may be Laurentian, Algoman, or Killarney in age. The writer is inclined to accept F. F. Grout's opinion[5] that the stock is more likely to be Algoman than Laurentian or Killarney but has no conclusive evidence.

The intrusive occupies an area 6 miles long and $2\frac{1}{2}$ miles wide, extending in a northeast-southwest direction. Poohbah Lake itself covers the greater part of this area, and, except at the east end, the contacts are roughly parallel to the present lake shore.

There is a smaller, narrow, elongate intrusive at Wink Lake, immediately west of Poohbah Lake. It is areally distinct from the Poohbah stock but may be connected with it at depth.

Quartz-biotite schist and its varieties form the country rock. The schist is typically medium- to fine-grained, but there are locally coarser facies. In a few exposures where quartz greatly predominates over biotite, the country rock is not so schistose and takes on the appearance of a sandstone on the weathered surface.

The average mineralogic composition of the schist is about 50 per cent quartz, 25 per cent biotite, and 25 per cent albite and orthoclase. Where quartz ranges as high as 65 per cent, there is a corresponding decrease in the feldspar percentage. Biotite is more nearly constant. Microcline was observed as a minor constituent in one slide, but the major feldspars are invariably orthoclase and albite-oligoclase. Accessory minerals are titanite, magnetite, apatite, allanite, and zircon. Radiating tourmaline crystals occur in the schists on Lake "A." Sillimanite occurs between Wink and Poohbah lakes. Pyrite is megascopically identifiable in practically all specimens but is usually only

[5] "The Vermilion Batholith of Minnesota," *Jour. Geol.*, Vol. XXXIII (1925), p. 471.

in minor amounts. In the thin sections the pyrite shows a coating of hematite, and much of the pyrite has been altered to cubic hematite pseudomorphs. Small garnets occur locally in the schists. One section from a contact at the east end of Poohbah Lake showed 5 per cent sodic amphibole analogous to that in the alkalic intrusive. Apparently there was some seepage of vapors from the main intrusive into the country rock.

Hornfels is a common rock facies at all contacts, in and adjacent to roof pendants, and in xenoliths. The largest roof pendant observed was approximately 30 feet long and is located on the south shore of the small heart-shaped island, $\frac{1}{2}$ mile northwest of the north end of island "D." The hornfels contains the same essential minerals as the quartz-biotite schist but a wider variety of accessory and secondary minerals. Hypersthene, rutile, chlorite, sericite, epidote, and leucoxene are common accessory and secondary minerals. Pyrite is more abundant in the hornfels than in the schists. One section shows chlorite after biotite, with a sagenitic network of rutile needles.

The quartz-biotite schists commonly contain a little injected granitic material but not sufficient to warrant calling them "injection gneisses." True bedding of the schists can only occasionally be determined by gradational grain size and cross-bedding.

Contacts between the schists and the intrusive were not observed in the north, south, or west, where they are marked by deep valleys, muskeg, and by abrupt changes in vegetation. Actual contacts were observed only between Berniece and Poohbah lakes. Here the contacts are typically intrusive and irregular; the intrusive engulfs schists, develops hornfels, and sends off a few small quartz-free pegmatites and aplites. Veins of pegmatite and aplite occur sparsely at contacts but were observed elsewhere in only two places. They are less numerous around this alkalic stock than around most granitic stocks.

The extent and relations of the stock east of Berniece Lake are largely unknown because of drift cover.

PETROGRAPHY OF THE INTRUSIVE

The rocks of the intrusive in the Poohbah Lake area may be divided into nine varieties as follows: (1) malignite, (2) porphyritic

alkalic syenite (and porphyritic nepheline syenite), (3) nepheline syenite, (4) alkalic syenites (some albite-rich), (5) shonkinite and porphyritic shonkinite, (6) hornblende syenite, (7) melteigite, (8) alkalic pyroxenite, and (9) granite, including pegmatite and aplite. The varieties are all intimately related, the contacts being gradational. Field gradations point to one main intrusive having different facies, all products of a common reservoir. Contacts between varieties were delineated only for the malignite, and that with difficulty because of the abundant drift.

All the above rock facies occur in the Poohbah Lake intrusive, excepting the hornblende syenites which predominate in the Wink Lake intrusive, in association with minor amounts of shonkinite and alkalic syenite. The Wink Lake mass is less alkalic than the Poohbah stock. None of the rocks contains nepheline, and not all the pyroxene is alkalic. The syenite mass at Wink Lake may be a sill, parallel to the Poohbah contact, i.e., swinging due east from the south end of Wink Lake. Traverses were made in 1939 to find this easterly extension, but no evidence was found. Outcrops of the several facies are shown on Figure 1 by numbers.

1. MALIGNITES (JOHANNSEN 3117P)[6]

Malignites occur sporadically along the shore of Poohbah Lake, notably on the point due west of the center of island "D," and on the point southwest of island "D." They occur in minor amounts on the point southeast of island "F." In the first two localities mentioned the malignites are intimately mixed with nepheline syenites—the latter differing from the malignites only in that they contain less than 50 per cent mafic minerals.

Megascopically the malignites (Fig. 2, *A*) are pitted mafic granitoid rocks. The dominant mineral is a pyroxene which occurs in elongated prisms. Orthoclase and nepheline form a dull gray groundmass for the pyroxene prisms. Yellowish-green apatite stands out on both fresh and weathered surfaces in rounded aggregates up to one-eighth inch in diameter. Titanite is easily recognized megascopically. Small biotite books are common.

[6] Albert Johannsen, *Petrography* (Chicago: University of Chicago Press, 1931), p. 115.

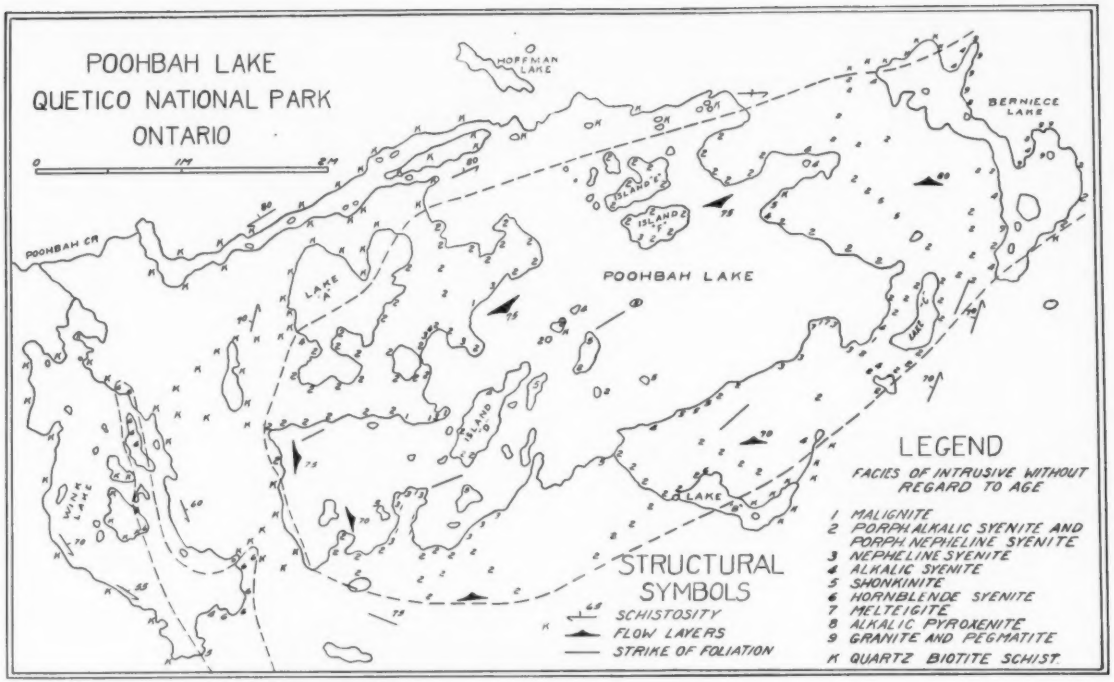
POOHBAH LAKE
QUETICO NATIONAL PARK
ONTARIO
1M
2M
HOFFMAN LAKE
BERNIECE LAKE
ISLAND E
ISLAND C
ISLAND D
POOHBAH CR.
POOHBAH LAKE
LAKE A
WINK LAKE
LAKE
LEGEND
FACIES OF INTRUSIVE WITHOUT REGARD TO AGE
1 MALIGNITE
2 PORPH. ALKALIC SYENITE AND PORPH. NEPHELINE SYENITE
3 NEPHELINE SYENITE
4 ALKALIC SYENITE
5 SHONKINITE
6 HORNBLENDE SYENITE
7 MELTEIGITE
8 ALKALIC PYROXENITE
9 GRANITE AND PEGMATITE
K QUARTZ BIOTITE SCHIST
STRUCTURAL SYMBOLS
SCHISTOSITY
FLOW LAYERS
STRIKE OF FOLIATION

FIG. 1

A

B

C

FIG. 2.—*A*, Typical malignite—crystals of pyroxene and apatite set in a felsic matrix. Occurs immediately west of island "D." Natural size. *B*, Vermicular intergrowth of nepheline in orthoclase, in nepheline syenite. ×75. Crossed nicols. *C*, Zoned feldspar crystals in porphyritic alkalic syenites west of island "D." Natural size.

In thin section the malignites are hypautomorphic granitoid. The aegerine-augite occurs as eight-sided prisms with a pronounced elongation in the direction of the *c*-axis. Approximately half of the malignite sections show pyroxene poikilitically enclosed in orthoclase. A striking textural feature (Fig. 2, *B*) is the vermicular intergrowth of nepheline in orthoclase. Much of the intergrown nepheline has altered to a dusty brown, almost opaque zeolite, possibly thomsonite. Lawson[7] and J. J. Sederholm[8] have already described this and similar intergrowths. Perthitic intergrowths are uncommon in the malignites, though one section shows a trace of vein perthite.

Lawson[9] reports that the malignites show three facies, namely, nepheline-pyroxene malignite, garnet-pyroxene malignite, and amphibole malignite. According to Johannsen's classification the nepheline-pyroxene malignite is correctly called "malignite." Lawson's "garnet-pyroxene malignite" and "amphibole malignite," both of which he described also as being porphyritic, are considered by the writer to be porphyritic alkalic syenites. The amphibole of the amphibole malignite is a deuteric alteration product of the pyroxene. Both amphibole and garnet occur scattered throughout the stock and are not restricted to any one locality.

The essential minerals in the malignite as determined microscopically in twelve sections are aegerine-augite 45–70 per cent, silicic feldspar 10–38 per cent, nepheline 6–25 per cent, biotite 3–12 per cent, apatite 4–10 per cent, and, in one section only, melanite garnet 8 per cent. Nearly all the aegerine-augite is both twinned and zoned. The inner zone is almost colorless or pale green, whereas the outer zone is grass-green and rich in the aegerine molecule. Sodic amphibole, though it is a common deuteric alteration product of aegerine-augite in the other varieties of rock in the area, occurs only as an accessory mineral in the malignites. Biotite and amphibole do not commonly occur in the same section.

Orthoclase is the chief feldspar, although microcline and albite occur in small amounts. Perthites are not nearly so well developed in the malignites as they are in the other facies of the stock. Small

[7] *Op. cit.*, p. 348.

[8] "On Synantectic Minerals," *Comm. geol. Finland, Bull. 48* (1916), p. 83.

[9] *Op. cit.*, p. 342.

apatite rods are commonly included in the orthoclase. The feldspars in most of the rocks are quite fresh; where alteration does occur the secondary minerals are kaolinite and sericite. Some of the orthoclase poikilitically encloses all other constituents.

Nepheline occurs as characteristic hexagonal crystals. Nearly all the nepheline has been altered to an indistinct mass of thomsonite and probably a little feldspar.[10] Some of the nepheline in the stock is still optically identifiable as such, but this is true only in the nepheline syenites. One malignite section shows a zeolite vein which closely resembles the thomsonite of the altered nepheline. Where the nepheline has been altered to a zeolite, it is assumed that this zeolite is always thomsonite.

Biotite is a minor constituent in the malignites. In some it occurs in flakes and books, but in many it is a deuteric alteration product of the pyroxene. Commonly the pyroxene has biotite inclusions and biotite replacements along the cleavage. The biotite is a magnesium-rich variety ($\gamma = 1.59 \pm 2$) and is pleochroic from a light olive-green to almost black. The bent and twisted biotite is the only sign of deformation within the alkalic intrusive.

Apatite also is a minor constituent but is commonly too abundant to be called an accessory. The large apatite grains are characteristically fractured. Small apatite rods are common as inclusions in the feldspars. Haloes occur around most apatite and titanite inclusions in the biotite.

Accessories in the malignite are magnetite, titanite, and garnet. The magnetite may possibly be titanium-rich (ilmenite), because rings of titanite were observed around it. Titanite characteristically occurs as large wedges. Garnet, discovered in one section, grew in two generations; some of the crystals show a ring of titanite, and the titanite in turn is encircled by more garnet.

No microscopic work was done on the garnet, but it is the melanite variety, as Lawson reports.[11] It is brown, and some of it is slightly birefringent. The melanite and titanite are closely associated, and their relationship in some cases is such that it suggests a genetic connection. In thin section the melanite garnet and titanite can be dis-

[10] X-ray determination by Dr. J. W. Gruner.

[11] *Op. cit.*, p. 355.

tinguished only under crossed nicols. Joseph Barrell reports a similar relation in Montana:

> The titanite occurs in anhedral grains, and these are so closely intergrown with a brown garnet that it is only under polarized light that they can be clearly separated. This close association of the crystals suggests that before crystallization the two may have existed in segregations of somewhat similar molecules, differing from each other in that one kind possessed iron, the other titanium, the two substances on crystallization being forced to separate owing to their different habits of crystallization.[12]

2. PORPHYRITIC ALKALIC SYENITES

These are by far the most abundant rocks in the intrusive. They form over half of the outcrops on the shoreline proper, and back from shore toward the contact with the country rock little else is exposed. The porphyritic alkalic syenite consists of large albite phenocrysts set in a granitoid groundmass of ferromagnesian minerals. The phenocrysts (Fig. 2, *C*) range in size up to at least 2 inches by $1\frac{1}{2}$ inches by $\frac{1}{2}$ inch. Some of them show excellent zoning, possibly repeated, but are cloudy with decomposition products. This zoning is not conspicuous microscopically. Orthoclase and microcline occur as phenocrysts too. Perthites are common and reach their maximum development in the porphyritic rocks. They are either entirely absent from, or in mere traces, in the nepheline-bearing granitoid rocks. They are confined to the porphyritic border phases and do not occur in the granitoid center of the stock.

The groundmass of the porphyritic alkalic syenite consists chiefly of aegerine-augite, biotite, and sodic hornblende. The hornblende and biotite do not commonly occur together. The aegerine-augite and biotite are similar in characteristics to those described in the malignites. Sodic hornblende was observed in only one section of malignite and then as an accessory; but it occurs in all the porphyritic alkalic syenites and ranges from 3 to 12 per cent, with an average of 5 per cent. It is deuteric after aegerine-augite. It has positive elongation and is, therefore, not of the riebeckite-arfvedsonite series. The absorption formula is $Z > Y > X$, and its pleochroism X = green-brown, Y = yellow-brown, and Z = blue-green. Some other

[12] "The Elkhorn Mining District," *U.S. Geol. Surv. 22d Ann. Rept.*, Part II (1900–1901), p. 520.

amphibole in the stock has negative elongation and approaches the riebeckite-arfvedsonite series, but, whereas its pleochroism is almost identical with that of the sodic hornblende, its absorption formula could not be determined because of its deep pleochroism and the scarcity of material.

Accessory minerals are similar to those in the malignites, except that allanite is added. Some specimens contain minute amounts of nepheline or its alteration products. Carbonate is partly an alteration product and partly introduced together with the prevalent pyrite.

3. NEPHELINE SYENITES

Nepheline syenites occur intimately mixed with the malignites. Nepheline forms 7–37 per cent of the rocks examined microscopically. The vermicular intergrowth of nepheline and orthoclase is abundant in these rocks. Practically all the nepheline has been altered to thomsonite; one section was visibly uniaxial but cloudy in spots with paragonite or sericite. An excellent gel is obtained when the nepheline is digested with hydrochloric acid and the decanted liquid evaporated. Some of the feldspathoid is isotropic. This gave a faint chlorine test but a heavy sulphate test, indicating either hauynite or nosean. Microchemical tests for soda and lime proved the mineral to be hauynite. The hauynite has a gray color in thin section and is not identifiable megascopically. Blank determinations were run on all the chemical analyses.

One section shows a blue mineral which was first thought to be fluorite. It is isotropic, and its index is less than that of balsam. The relief was compared with that of known fluorite and hauynite, and it seems to be hauynite rather than fluorite. These hauynite-bearing rocks are intimately mixed with the normal nepheline syenites and malignites on the point due west of the center of island "D."

4. ALKALIC SYENITES

The alkalic syenites are the granitoid equivalents of the porphyritic alkalic syenites. Some of the alkalic syenites contain as much as 85–90 per cent albite feldspar. They closely approach albitite, or albite anorthosite, a term which was used in the field. These albite syenites differ from the alkalic syenites only in that they contain less

aegerine-augite and sodic amphibole and few if any phenocrysts. The alkalic syenites contain small quantities of orthoclase and microcline, usually as perthitic intergrowths with the albite. Both the aegerine-augite and sodic amphibole syenites contain traces of nepheline. The alkalic syenites north and east of the shonkinite on Wink Lake contain 22 per cent of aegerine-augite and 8 per cent of sodic hornblende.

5. SHONKINITES

Shonkinites occur in variable amounts on the islands south and east of island "D" and at the south end of Wink Lake. They also occur on the shore of Poohbah Lake, due north of Lake "B." This rock facies differs from malignite in the absence of nepheline. The shonkinites are closely related to the porphyritic alkalic syenites. They occur adjacent to the porphyritic facies and are petrographically similar except for the absence of the feldspar phenocrysts. Some of the shonkinite is porphyritic, differing from the porphyritic alkalic syenites in containing 50 per cent or more of ferromagnesian minerals—aegerine-augite, sodic amphibole, and biotite.

The shonkinite at the south end of Wink Lake consists of 52 per cent augite, 22 per cent biotite, and 22 per cent albite and orthoclase. It resembles the shonkinites of Poohbah Lake, except for the fact that the pyroxene is augite rather than aegerine-augite.

6. HORNBLENDE SYENITES

Hornblende syenites compose the major part of the Wink Lake intrusive. It is a typical hornblende syenite consisting of silicic feldspar and hornblende, with minor amounts of biotite. Quartz was not noted.

7. MELTEIGITE (JOHANNSEN 3125P)[13]

Melteigite crops out on the point southeast of island "F." Megascopically it is a pitted, mafic, granitoid rock with white specks of nepheline set in a crystalline mass of aegerine-augite. Biotite flakes are fairly abundant in the hand specimen. A Rosiwal analysis of the section gives aegerine-augite 52–60 per cent, biotite 30–33 per cent, nepheline 13–19 per cent, with magnetite, titanite, and apatite as accessories. Thomsonite and sericite are the alteration products of the nepheline. Pyrite has been introduced.

[13] Johannsen, *op. cit.*, pp. 327–31.

The outstanding feature of this rock is the lack of feldspar; in other respects it is like the malignite. The rocks on the point southeast of island "F" from west to east in the distance of a quarter of a mile are alkalic pyroxenite, malignite, melteigite, and nepheline syenite.

8. PYROXENITE

Pyroxenites crop out on the east shore of Berniece Lake. The alkalic pyroxenite is a highly mafic, granitoid rock. Megascopic constituents are pyroxene, large flakes of biotite, and small wedges of titanite. A thin section reveals aegerine-augite 90 per cent, biotite 4 per cent, with secondary kaolinite and sericite. Accessories are titanite, apatite, and magnetite.

9. SYENITE, GRANITE, PEGMATITE, AND APLITE

These varieties outcrop on the east shore of Berniece Lake. The west shore is mostly porphyritic alkalic syenite, though pegmatites were observed there, too. The relation of these quartz-bearing rocks to the alkalic ones is not known, and nothing is known of the area east of the shore. From the structure of the schists the writer believes that syenite and granite occupy the area immediately northeast of Berniece Lake.

CHEMICAL RELATIONS

Two new chemical analyses are presented—Nos. 1 and 5 of Table 1. They represent the basic and the acidic extremes of the alkalic stock, and they are, respectively, a melteigite and a porphyritic alkalic syenite. Five analyses are now available from this stock, covering the range of composition of the different facies. An interesting point is that the high-silica rocks occur in the porphyritic border facies and that rocks low in silica (rich in feldspathoids) occur in the central parts. Taken as a whole, the analyses represent a suite of rocks low in silica and alumina and rich in magnesia, lime, and alkalies. Chemically the Poohbah stock is not quite like any other known alkalic intrusive, but individual rocks resemble facies of the Monteregian Hills[14] and of the Highwood Mountains.[15]

The norms of these rocks are tabulated in Table 2. The norm of

[14] F. D. Adams, "The Monteregian Hills," *Jour. Geol.*, Vol. XI (1903), pp. 254–69.

[15] L. V. Pirsson, "Igneous Rocks of the Highwood Mountains," *U.S. Geol. Surv. Bull. 237* (1905), p. 123.

the melteigite is almost wholly different from the mode. The outstanding feature of Table 2 is that there is a gradual increase in the

TABLE 1

ANALYSES OF ROCKS FROM POOHBAH LAKE

	1	2	3	4	5
SiO_2	45.96	47.85	51.38	51.88	57.14
Al_2O_3	9.57	13.24	15.88	14.13	16.42
Fe_2O_3	2.79	2.74	1.48	6.45	2.10
FeO	4.56	2.65	4.37	0.94	2.64
MgO	14.79	5.68	4.43	3.44	2.63
CaO	11.85	14.36	8.62	10.81	5.53
Na_2O	2.19	3.72	7.57	6.72	4.33
K_2O	4.12	5.25	4.20	4.57	6.39
H_2O+	1.93	2.74	0.42	0.18	0.36
H_2O-	0.15				0.06
CO_2	0.45	.....	.....	.....	n.d.*
TiO_2	0.50	.....	0.12	0.33	0.71
P_2O_5	0.20	2.42	0.98	0.96	0.85
F	n.d.	.....	.....	.....	n.d.
S	0.04	.....	.....	.....	0.09
Cr_2O_3	0.08	.....	.....	.....	0.00
MnO	0.13	.....	.....	.....	0.08
BaO	0.12	.....	.....	.....	0.22
Total	99.43	100.65	99.45	100.41	99.56

* About 0.10 per cent.

1. Melteigite. Aegerine-augite 52 per cent, biotite 33 per cent, nepheline 13 per cent, with kaolinite, zeolite, epidote, zoisite, and carbonate as alteration products, and magnetite, apatite, and titanite as accessories. Rossweinose, IV. 1.2.2. (Johannsen 3125P). C. C. Allen, analyst.

2. Nepheline-pyroxene malignite. Aegerine-augite 48 per cent, orthoclase 21 per cent, nepheline 20 per cent, apatite 5.8 per cent, with biotite and titanite as accessories totaling 3 per cent. Sodipotassic malignase, III. 7.1.3. (Johannsen 3117P). F. L. Ransome, analyst. A. C. Lawson, *Bull. Dept. Geol., Univ. Calif.*, Vol. I, No. 12 (1896), p. 350.

3. Amphibole malignite (considered by writer to be porphyritic alkalic syenite). Malignose, III. 7.1.4., J. W. Sharwood, analyst. A. C. Lawson, *op. cit.*, p. 359.

4. Garnet-pyroxene malignite (considered by writer to be porphyritic alkalic syenite). Pilandose, III. 6.1.4., W. C. Blasedale, analyst. A. C. Lawson, *op. cit.*, p. 356.

5. Porphyritic alkalic syenite. Orthoclase and microcline 75 per cent, aegerine-augite 10 per cent, sodic hornblende 10 per cent, biotite 3 per cent, and apatite, titanite, and magnetite as accessories. Monzonose II. 5.2.3. (Johannsen 2113P). C. C. Allen, analyst.

normative diopside from the acidic to the basic facies. The changes are in agreement with the silica content of the five rocks of Table 1.

The silica-variation diagram, Figure 3, shows some of the oxides

plotted against silica. Analyses 3 and 4 have a similar silica content, but their alumina, lime, and magnesia percentages differ radically. In general, as SiO_2 and Al_2O_3 rise, the CaO and MgO fall, but the Al_2O_3 and CaO are not entirely regular.

STRUCTURE

The Poohbah intrusive has a roughly elliptical shape. The structure of the country rock conforms to the shape of the stock. The schistosity parallels the bedding, and both dip inward, making the

TABLE 2

NORMS

	1	2	3	4	5
Orthoclase	2.22	21.96	25.02	27.24	37.81
Albite	.....	.....	5.76	7.86	27.77
Anorthite	4.17	3.89	.....	.....	6.39
Nepheline	9.94	17.04	28.40	21.02	4.83
Leucite	17.44	7.20	.....	.....	.....
Olivine	16.52	.....	3.18	.....	2.81
Diopside	40.32	35.63	29.74	18.38	12.91
Acmite	.....	.....	4.16	8.78	.....
Sodium metasilicate	.....	.....	0.37	.....	.....
Wollastonite	.....	2.67	.....	9.74	.....
Magnetite	4.18	3.94	.....	2.09	3.02
Ilmenite	0.91	.....	0.30	0.61	1.37
Apatite	0.34	5.71	2.35	2.35	2.02
Hematite	.....	.....	.....	1.92	.....

stock funnel-shaped in section. Crystal orientation in the stock indicates that the walls are very steep, though dipping inward. The mass is elongated northeast-southwest, and throughout most of it the strike of foliation is in the same direction as the elongation. In Figure 1 structure symbols show the foliation in both schist and intrusive.

The Wink Lake intrusive appears to be Sill-like in shape, conforming to the structure of the country rock, which dips steeply east. It is probably continuous with the Poohbah mass at depth, a condition which is inferred from the areal proximity and the similar alkalic nature of the two masses.

Pegmatites and aplites are found on both shores of Berniece Lake, but the development on the west shore is sparse and sporadic. Those on the east shore are probably related to the granites, which occur farther to the northeast. The relation of this granitic body to the

Poohbah alkalic rocks is not known because of the drift cover, although the granitic mass is supposed to be at least slightly later in age.

ORIGIN OF THE ALKALIC ROCKS

The geology of the Poohbah Lake area may be summed up as follows: an alkalic stock some 6 miles long and $2\frac{1}{2}$ miles wide intruded a quartz-biotite schist which is the country rock all around the

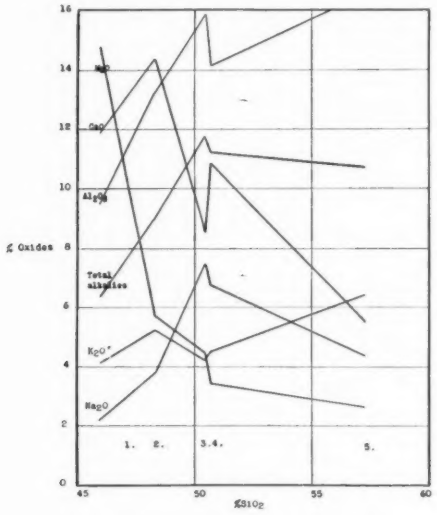

FIG. 3.—Silica variation diagram

stock. The stock consists of several lithologic and textural facies, ranging from rocks rich in aegerine-augite to those almost pure feldspar. Only the intermediate facies contain nepheline and other feldspathoids.

The origin of these alkalic rocks can best be explained by crystallization differentiation. The formation of free silica by the differentiation of a basaltic magma has been regarded as due to several factors at various stages, most important among which is the early separation of olivine and its failure to react. Its formation can be prevented by the reaction of olivine and magma, which may occur if the olivine crystals are stirred in a large reservoir to prevent their

settling and segregation, or by rapid cooling over the temperature range in which olivine might crystallize out. If either of these conditions prevails, a trachytic rather than a granophyric differentiate results.

Under certain conditions, depending upon the incongruent melting-point of orthoclase, a trachytic melt may pass to an alkalic line of descent.[16] Leucite rather than orthoclase will precipitate first from a melt lacking excess silica. Under normal conditions this reacts to form orthoclase. However, there may be segregation of an appreciable amount of the leucite in a part of the magma reservoir. Then the remainder, with some of the leucite crystals, will pass to normal syenites and granites by reaction of the leucite to form orthoclase and by the precipitation of the excess silica as quartz. That part of the magma in which leucite crystals were concentrated will pass toward an alkalic line of descent by the pseudo-leucite reaction, the remaining liquid reacting with the leucite to form orthoclase and nepheline.

Rocks in the Poohbah stock range in composition from alkalic pyroxenite to albite anorthosite or albite-rich syenite. The several facies occur irregularly throughout the stock, a condition which is best explained by differentiation. The nepheline-rich rocks occur in localized areas, perhaps analogous to those in which leucite segregated in accordance with the above theory. The zoned pyroxenes and feldspars, deuteric amphibole and biotite, point to a slowly cooling magma, whose composition was gradually becoming more trachytic. In thin sections it is seen that the last minerals to crystallize were nepheline and orthoclase.

The assimilation theory has been advanced to account for the origin of alkalic rocks. The three distinct processes involved are as follows:

1. Solution of limestone by magma, leading to direct formation of feldspathoids by desilication of feldspar molecules.

2. Sinking of heavy lime silicates and complementary rise of a light alkalic fraction under control of gravity.

3. Formation of alkaline carbonates and rise of these towards the roof of the magma chamber, where carbon dioxide is replaced by silica.[17]

[16] N. L. Bowen, *The Evolution of Igneous Rocks* (Princeton: Princeton University Press, 1928), pp. 227–57.

[17] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill Book Co., Inc., 1933), pp. 498–99.

In an article which mentions the Poohbah Lake alkalic mass, S. J. Shand states, first, that "a body of highly alkaline rock may be formed at a distance from any visible body of carbonate rock. Thus the absence of a limestone from the immediate neighborhood of a feldspathoidal rock cannot be regarded as proof that limestone played no part in its formation." He continues: "I have no hesitation in predicting that further work in Poohbah Lake . . . . will eventually furnish evidence of the presence of a limestone in contact with the alkaline eruptive."[18]

If assimilation did occur, the stock with its siliceous border phase would have been enriched rather than impoverished in silica. Field investigation reveals that some assimilation of the siliceous country rock did take place. Hornfels inclusions and roof pendants were observed. The malignites and nepheline syenites occur in the central part of the stock, and the porphyritic alkalic syenites form the border phases. This relationship would suggest that some enrichment in silica had occurred in the border rocks, lacking which, feldspathoidal rocks might also have been found here.

The Poohbah Lake stock is a fairly large one, having a surficial area of some 15 square miles. It is alkalic in all its facies, which contain variable amounts of aegerine-augite and sodic amphiboles, and the central part of the stock is composed of rocks containing nepheline and other feldspathoids as well. To account for this alkalic nature by the assimilation theory would require the presence of a fairly large limestone body. However, no limestone or high-calcium rocks were observed in the Poohbah Lake area. None has been reported by other workers in or adjacent to that area. Quartz-biotite schist surrounds the stock almost completely. The possibility that limestone occurs at depth or that the Poohbah stock replaced a limestone lens completely is remote. There is, therefore, no evidence in support of Daly's assimilation theory in this area.

H. G. Backlund[19] has selected seven alkalic bodies whose wall rock is free from carbonate rocks and in each case found that the core rock was most desilicated and that, the larger the mass, the more extreme

[18] "Limestone and Alkalic Rocks," *Geol. Mag.*, Vol. LXVII (1930), pp. 415–27.

[19] "On the Mode of Intrusion of Deep-seated Alkaline Bodies," *Upsala Univ., Geol. Inst. Bull.*, Vol. XXIV (1932), pp. 1–14.

the undersaturation. He suggests a reaction series which differs from that of Bowen in that the mafic minerals show a continuous isomorphous series, while the felsic series, starting with nepheline, is discontinous. He further contends that the early crystallization of felsic minerals and their strong tendency to rise to the top of the magma chamber preclude any upward escape of gas. The superheat and fluxing action of the gases, which are thus forced to escape laterally, would induce a reaction with the gneissic and siliceous country rocks, leading to saturation in the border phase. This might explain the saturated border facies and undersaturated core of the Poohbah stock, but the studies on crystallization sequence in thin sections do not support the premises of this theory.

Grout[20] has made the suggestion that the Poohbah stock and several other adjacent alkalic stocks may be satellites of the Vermilion batholith. The other bodies in question are the Vermilion Lake stock, the Linden stock, and the syenites of Snowbank and Kekequabic lakes. These relations suggest the generalization that alkalic differentiates are widely characteristic of Algoman granites in Minnesota. The Vermilion batholith may represent the main magma chamber, in which the bulk of the magma followed the rhyolitic line of descent. The several types of alkalic rocks of the satellites may have crystallized from a magma which derived from the main body but followed a trachytic line of descent and achieved varied degrees of differentiation before consolidating.

The Poohbah Lake stock appears to be another example which supports Bowen's theory that alkalic rocks have originated by the process of crystallization differentiation.

ACKNOWLEDGMENTS.—The writer is indebted to Dr. F. F. Grout for valuable assistance both in the laboratory work and in interpreting the results. Mr. L. A. Smith acted as field assistant during both seasons. An X-ray analysis was performed by Dr. J. W. Gruner, and the chemical analyses were made under the supervision of Dr. R. B. Ellestad. Acknowledgment is also due to the Canadian Geological Survey for the loan of forty thin sections. Messrs. R. E. Folinsbee and J. C. Scott helped with the laboratory and map work.

[20] *Op. cit.*, pp. 467–87.

THE SYSTEM $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$

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ABSTRACT

The high-temperature equilibrium relationships in the systems $NaAlSi_3O_8$-$CaSiO_3$, $NaAlSiO_4$-$CaSiO_3$, and $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ have been investigated by the quenching method. The results have been tabulated, and equilibrium diagrams have been drawn up. The petrologic significance of this investigation is discussed.

INTRODUCTION

This investigation is concerned with the high-temperature equilibrium relationships, at atmospheric pressure, of the three silicates —$NaAlSi_3O_8$, $CaSiO_3$, and $NaAlSiO_4$. These three silicates were chosen for study because they constitute the fundamental molecules of three rock-forming minerals, albite, wollastonite, and nepheline, respectively. Albite and nepheline are well-known primary constituents of igneous rocks, whereas wollastonite is typically a contact metamorphic mineral. However, wollastonite does occur occasionally as a primary mineral in certain of the alkaline rocks, and in such cases it is usually accompanied by albite and nepheline. Two of the silicates involved in this study, $CaSiO_3$ and $NaAlSiO_4$, exhibit polymorphism. There is but a single recorded natural occurrence of pseudowollastonite, the high-temperature form of $CaSiO_3$. Carnegieite, the high-temperature modification of $NaAlSiO_4$, has never been encountered in nature.

The investigation includes the systems $NaAlSi_3O_8$-$CaSiO_3$, $NaAlSiO_4$-$CaSiO_3$, and $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$. The relation of these systems to the general quaternary system soda-lime-alumina-silica is shown in Figure 1. There is pictured a hollow tetrahedron with the soda-lime-silica face removed, in order to afford a view of the interior. The $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ system forms an internal plane of the tetrahedron, this plane being represented by the triangular area with apices designated as AB, WO, and NE.

Sixty mixtures in all were synthesized, and these were subjected to

thermal study by the quenching method. Approximately three hundred individual runs were carried out. The data from the more significant of these runs are presented in tabular form. From these data have been prepared the equilibrium diagrams of the various systems investigated.

EXPERIMENTAL PROCEDURE

PREPARATION OF MIXTURES

Homogeneous glasses, corresponding in composition to the sixty desired mixtures, were first made up. The purest available raw materials were used for this purpose. These were: sodium carbonate monohydrate, precipitated calcium carbonate, aluminum hydroxide, and specially selected vein quartz. Preliminary heating ensured the anhydrous condition of the reagents. Glasses were made up either directly from these materials or by mixing two or more previously prepared glasses. In the preparation of those glasses made up directly from the oxides and carbonates, especially those rich in soda, preliminary heating at low temperature was resorted to before the mixtures were raised to their fusion temperatures. This precaution effected gentle liberation of carbon dioxide and prevented appreciable volatilization of soda.

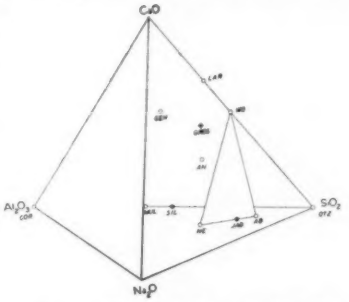

FIG. 1.—The soda-lime-alumina-silica tetrahedron. Compositions of minerals that are included within this quaternary system are plotted in mole per cent. The symbols and abbreviations have the following significance: LAR, larnite; WO, wollastonite; GEH, gehlenite; GROS, grossularite; AN, anorthite; COR, corundum; MUL, mullite; SIL, sillimanite; NE, nepheline; JAD, jadeite; AB, albite; QTZ, quartz; ○, compound has been prepared synthetically; ⊗, compound has not been prepared synthetically.

From two to six fusions of each mixture, with intermediate grinding and mixing, were necessary to bring about uniformity of composition. A set of standardized refractive index liquids and a petrographic microscope afforded a simple and rapid method of testing the homogeneity of the glasses and of checking their compositions.

The glass of each mixture possesses its own particular index of refraction. As each mixture was prepared, the refractive index of its glass was determined, and a chart showing the variation of index of refraction with composition was plotted. This chart served as a check on the composition of each additional mixture that was prepared. Furthermore, all of the grains of the powder of a uniform glass will have the same index of refraction, and all will therefore match the same liquid. Failure to do so indicated that further fusion was necessary to effect homogeneity. In Figure 2 is presented the index of refraction chart for the system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$. The final step in the preparation of the mixtures for thermal investigation was the devitrification of the glasses. This simply involved heating each glass for about a half-hour at a temperature somewhat below its temperature of melting.

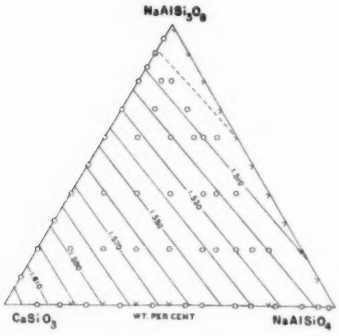

FIG. 2.—Index of refraction chart for glasses of the system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$.

THERMAL INVESTIGATION

In this investigation the quenching method, as developed and employed in the Geophysical Laboratory of the Carnegie Institution of Washington, was used exclusively. The details of the procedure have been described repeatedly in publications from the Geophysical Laboratory and need not be presented here. Briefly, the method is as follows: A small charge of a given mixture is held at a constant temperature until equilibrium is attained. By dropping it into cold mercury the charge is instantaneously cooled from its elevated temperature to that of the mercury, and the equilibrium condition at the elevated temperature is thereby "frozen." After the quenching operation a mount of the powdered charge is examined under the microscope for the purpose of identifying the phases present. The whole procedure is repeated on a number of charges of a given mixture at various temperatures. In this manner it is possible

to ascertain, within narrow limits, the temperature of a change of phase or of the appearance or disappearance of a phase. In general, these transformation temperatures are located with an accuracy of plus or minus two centigrade degrees and are expressed in terms of the revised gas-thermometer scale of A. L. Day and R. B. Sosman.[1] From the critical data so obtained the various equilibrium diagrams have been drawn up. Tables of these thermal data and the equilibrium diagrams prepared from them are presented in the later pages of this report.

MICROSCOPIC EXAMINATION OF CHARGES

The quenched charges were examined microscopically to identify the phases present. A pinch of the powdered charge was studied in each case by ordinary immersion methods. The glass phase was easily recognized, being isotropic and homogeneous, and formed the matrix for any crystals which might be present. The crystalline phases, five in number, were readily distinguished from one another. Observation of such features as the relief, crystal outline, sign of elongation, and birefringence was all that was necessary for identification. There was no need to make accurate measurements of the refractive indices. The distinctive features of each of the five crystalline phases, as used in their identification in this study, are summarized in the following paragraphs.

Plagioclase.—The results of the thermal study indicated that the feldspar crystals were not pure albite but rather a plagioclase bearing a small amount of anorthite in solid solution. The refractive indices accordingly were probably very close to the values given by A. N. Winchell[2] for albite, which are as follows: $\alpha = 1.525$; $\beta = 1.529$; $\gamma = 1.536$. The plagioclase appeared as well-formed crystals of marked tabular habit, with the brachypinacoid $b(010)$ showing the greatest development. Viewed on edge, they appeared as long warped laths with low to moderate birefringence, negative elongation, and small extinction angles. The relief was high, owing to the relatively low indices of the enclosing glasses. The plates often

[1] "The Melting Points of Minerals in the Light of Recent Investigations on the Gas Thermometer," *Amer. Jour. Sci.*, Vol. XXXI (4th ser., 1911), pp. 341–49.

[2] *The Optic and Microscopic Characters of Artificial Minerals* ("Univ. Wis. Studies in Science," No. 4 [1927]), p. 144.

showed the six-sided outline typical of the $b(010)$ face of albite and exhibited much lower relief and birefringence, when thus oriented, than when seen on edge.

Pseudowollastonite.—The high-temperature form of $CaSiO_3$ is pseudohexagonal, being almost uniaxial, but its true symmetry is probably monoclinic. Its indices of refraction, as stated by J. B. Ferguson and H. E. Merwin,[3] are: $\alpha = 1.610$; $\beta = 1.611$; $\gamma = 1.654$. It formed more or less equant grains, which were usually of round or oval shape, although highly irregular, bulbous forms were often produced. Frequently, too, well-formed crystals were developed, and these appeared as hexagonal plates, which often departed widely from the form of the regular hexagon. These plates exhibited extremely low birefringence. When seen on edge, however, they appeared as laths with negative elongation and high birefringence. A peculiar type of twinning was observed in one of the runs. In this instance forms resembling perfect Maltese crosses were displayed.

Wollastonite.—Wollastonite is monoclinic and, according to Ferguson and Merwin,[4] possesses the following refractive indices: $\alpha = 1.616$; $\beta = 1.629$; $\gamma = 1.631$. It exhibited short rectangular laths, with positive elongation and low birefringence. Often these laths occurred in aggregates of parallel rows. Occasionally the rhombic outlines of a $b(010)$ face were observed. The mean refractive indices of the two forms of $CaSiO_3$ are very close in value, but differences in the birefringences and the signs of elongation served to distinguish one from the other.

Carnegieite.—This high-temperature form of $NaAlSiO_4$ exhibited a complete lack of crystal form. N. L. Bowen and J. W. Greig[5] have established its symmetry as isometric, and C. E. Tilley[6] has noted crystals of carnegieite which appear to belong to the isometric system. No euhedral development was noted in any of the runs carried out in this investigation. Invariably it appeared as rounded globules, frequently arranged in rosettes. Intricate twinning, occasioned

[3] "The Ternary System CaO-MgO-SiO_2," *Amer. Jour. Sci.*, Vol. XLVIII (4th ser., 1919), p. 83.

[4] *Ibid.*

[5] "The Crystalline Modifications of $NaAlSiO_4$," *Amer. Jour. Sci.*, Vol. X (5th ser., 1925), p. 204.

[6] "The Ternary System, Na_2SiO_3-$Na_2Si_2O_5$-$NaAlSiO_4$," *Min. u. Petrog. Mittheilungen*, Vol. XLIII (1933), p. 409.

by inversion at lower temperature to a triclinic modification, was seen in almost every case. Bowen[7] assigns to the latter form the following indices of refraction: $\alpha = 1.509$; $\gamma = 1.514$. The birefringence was consequently low. In every case the enclosing glass had a higher index than either of these values, causing the carnegieite to show pronounced negative relief.

Nepheline.—Nepheline is hexagonal, its characteristic habit being broad, rectangular, prismatic sections and hexagonal, basal sections. Bowen[8] determined the indices of refraction to be: $\omega = 1.537$; $\epsilon = 1.533$. The nepheline crystals encountered in this study were really solid solutions containing the albite molecule in addition to $NaAlSiO_4$. J. W. Greig and Tom F. W. Barth[9] were unable to decide as to what effect albite had upon the indices of refraction of nepheline on entering into solid solution in the latter. In the case of one of the solid solutions encountered in the present work, the value of ϵ was found to have been lowered to at least 1.530. This indicates that albite lowers the indices of nepheline, which is the behavior to be expected. It is possible that a very small amount of anorthite also enters into the solid solutions, since the feldspar of this system is not pure albite. The crystals showed in some cases positive and in others negative relief against the glass matrix and in some cases could scarcely be discerned. They exhibited low but perceptible birefringence, and the elongation was in most cases negative, although in a few runs it was positive. In the case of these latter, the positive elongation is due not to a change of the optical character of the nepheline solid solution from negative to positive but rather to an abnormal development of the base.

THERMAL DATA

THE BINARY SYSTEM $NaAlSiO_4$-$NaAlSi_3O_8$

This system has already been investigated by Greig and Barth,[10] and the diagram and discussion given here are based on their work. Their

[7] "The Binary System: $Na_2Al_2Si_2O_8$ (Nephelite, Carnegieite)-$CaAl_2Si_2O_8$ (Anorthite)," *Amer. Jour. Sci.*, Vol. XXXIII (4th ser., 1912), p. 564.

[8] *Ibid.*, p. 565.

[9] "The System, $Na_2O.Al_2O_3.2SiO_2$ (Nephelite, Carnegieite)-$Na_2O.Al_2O_3.6SiO_2$ (Albite)," *Amer. Jour. Sci.*, Vol. XXXV-A (5th ser., 1938), p. 111.

[10] *Ibid.*, pp. 94–112.

equilibrium diagram is reproduced in Figure 3. The melting temperatures of carnegieite and albite are located at 1,526° C. and 1,118° C., respectively. The eutectic lies at a temperature of 1,068° C. and at a composition of 76 per cent albite. Nepheline can accommodate as much as 33 per cent of albite in solid solution, whereas carnegieite solid solutions do not exceed 13 per cent of albite. Albite is able to take probably no more than 3 per cent of nepheline into solid solution. The normal inversion of nepheline to carnegieite takes place at 1,254 ± 5° C., but solid solution raises this to a maximum of 1,280° C. No intermediate compound was encountered within the liquidus range of this system, notwithstanding the fact that the mineral jadeite is intermediate in composition between albite and nepheline.

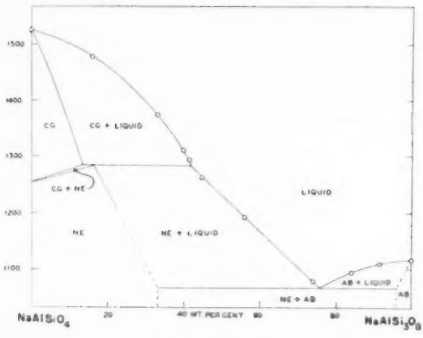

FIG. 3.—Equilibrium diagram for the system $NaAlSiO_4$-$NaAlSi_3O_8$. (After Greig and Barth.)

THE BINARY SYSTEM $NaAlSiO_4$-$CaSiO_3$

The results of the thermal investigation of this system are recorded in Table 1 and plotted in Figure 4. According to Greig and Barth,[11] the melting point of $NaAlSiO_4$ is 1,526° C. E. F. Osborn and J. F. Schairer[12] assign to $CaSiO_3$ a melting temperature of 1,544° C. These values were accepted for the present investigation. The eutectic is located at a temperature of 1,164 ± 2° C. and at a composition of 59 per cent $NaAlSiO_4$. This point was fixed by the intersection of liquidus curves and by the determination of the lowest temperature at which one of the two crystalline phases disappeared from the devitrified material.

The break in the liquidus curve of $NaAlSiO_4$, occasioned by the nepheline-carnegieite inversion, occurs at 1,267° C., which is 13 de-

[11] *Ibid.*, p. 99. [12] Unpublished data.

grees higher than the inversion temperature of the pure end member. This elevation of the inversion point must be attributed to solid solu-

TABLE 1

THERMAL DATA FOR THE BINARY SYSTEM
$NaAlSiO_4$-$CaSiO_3$

	Weight Per Cent		Time	Temperature (Centigrade)	Final Condition
	$NaAlSiO_4$	$CaSiO_3$			
Primary Phase $NaAlSiO_4$	90.0	10.0	30 min.	1,415°	CG and glass
			30	1,419	Glass
	81.8	18.2	45	1,313	CG and glass
			30	1,317	Glass
	75.0	25.0	45	1,254	NE and glass
			45	1,260	Glass
	70.0	30.0	45	1,238	NE and glass
			45	1,242	Glass
	60.0	40.0	45	1,175	NE and glass
			30	1,177	Glass
Primary Phase $CaSiO_3$	55.1	44.9	30	1,196	P-WO and glass
			30	1,200	Glass
	45.0	55.0	30	1,256	P-WO and glass
			30	1,260	Glass
	35.0	65.0	30	1,309	P-WO and glass
			30	1,313	Glass
	25.0	75.0	30	1,371	P-WO and glass
			45	1,375	Glass
	20.4	79.6	30	1,418	P-WO and glass
			30	1,422	Glass
	10.0	90.0	30	1,463	P-WO and glass
			30	1,467	Glass
Eutectic	70.0	30.0	10 hr.	1,162	P-WO, NE, and glass
			10	1,166	P-WO and glass
	55.1	44.9	10	1,162	P-WO, NE, and glass
			10	1,166	Glass
	45.0	55.0	10	1,162	NE, P-WO, and glass
			10	1,166	NE and glass
Nepheline-Carnegieite Inversion	81.8	18.2	14	1,265	NE and glass
			10	1,269	NE, CG, and glass
	90.0	10.0	14	1,265	NE and glass
			10	1,269	NE, CG, and glass

tion, and to greater solid solution in nepheline than in carnegieite. The extent of solid solution in nepheline was found to be between 5 and 10 per cent of the $CaSiO_3$ molecule. The amount of solid solu-

tion in carnegieite is therefore probably negligible and has been indicated in the diagram as nonexistent. It is possible that anorthite, rather than $CaSiO_3$, is the molecule which enters into solid solution in the nepheline. Anorthite might conceivably result from interaction between $NaAlSiO_4$ and $CaSiO_3$. This reaction would destroy the true binary nature of the system. But it would probably cause no more than a slight departure from binary behavior, and Figure 4 is based on the assumption that the system is truly binary.

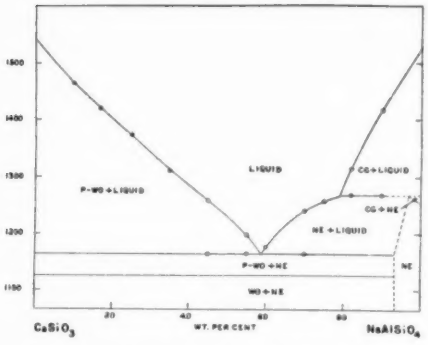

FIG. 4.—Equilibrium diagram for the system $NaAlSiO_4$-$CaSiO_3$.

In this system the wollastonite-pseudowollastonite inversion is a subliquidus change. Due to the sluggishness of reactions in the solid state and to the difficulty of identifying phases in completely devitrified material, no attempt was made to establish the inversion temperature. In the diagram the line marking the inversion has been placed at 1,124° C., on the basis of relations found in the system $NaAlSi_3O_8$-$CaSiO_3$. A possible second example of subliquidus equilibrium was considered in the study of this system. No intermediate compound was encountered in the temperature range within which the melting phenomena of the system occur. But it was thought possible that such a compound, corresponding in composition to the one-to-one molar combination of $NaAlSiO_4$ and $CaSiO_3$, might exist as a subliquidus phase. A mixture of this composition was prepared, and portions of it were devitrified at 800° C. and 925° C. The two preparations were subjected to X-ray analysis but yielded no evidence for the existence of the postulated intermediate compound.

THE SYSTEM $NaAlSi_3O_8$-$CaSiO_3$

The thermal data for this system have been tabulated in Table 2 and have been used in plotting the equilibrium diagram shown in

Figure 5. It is not a true binary system, since the composition of the various phases cannot always be expressed in terms of the two end members. All points on the liquidus curves lie above 1,118° C., the melting point of pure albite. No liquidus of albite exists; instead,

TABLE 2

THERMAL DATA FOR THE SYSTEM

$NaAlSi_3O_8$-$CaSiO_3$

	Weight Per Cent		Time	Temperature (Centigrade)	Final Condition
	$NaAlSi_3O_8$	$CaSiO_3$			
Primary Phase Plagioclase	95.0	5.0	6 hr.	1,125°	PLAG and glass
			6	1,127	Rare PLAG and glass
	90.0	10.0	6	1,126	Rare PLAG and glass
	85.0	15.0	5 hr.	1,168	P-WO and glass
			5	1,172	Glass
	80.0	20.0	1	1,208	P-WO and glass
			1	1,212	Glass
	70.0	30.0	45 min.	1,258	P-WO and glass
			1 hr.	1,262	Glass
	60.0	40.0	30 min.	1,297	P-WO and glass
Primary Phase $CaSiO_3$			30	1,301	Glass
	50.0	50.0	30	1,334	P-WO and glass
			30	1,338	Glass
	40.0	60.0	30	1,366	P-WO and glass
			30	1,370	Glass
	30.0	70.0	30	1,410	P-WO and glass
			30	1,414	Glass
	20.0	80.0	30	1,444	P-WO and glass
			30	1,448	Glass
	10.0	90.0	30	1,499	Rare P-WO and glass
	80.0	20.0	16 hr.	1,122	WO and glass
Wollastonite-Pseudowollastonite Inversion			12	1,124	WO, rare P-WO, and glass
			16	1,126	WO, P-WO, and glass
	60 0	40.0	16	1,122	WO and glass
			12	1,124	WO, rare P-WO, and glass
			16	1,126	WO, P-WO, and glass
	40.0	60.0	16	1,122	WO and glass
			12	1,124	WO, rare P-WO, and glass
			16	1,126	WO, P-WO, and glass

there is one of plagioclase. The liquidus of pseudowollastonite extends across the system as far as a composition of about 89 per cent albite. It is initially concave upward but becomes convex as the liquidus of plagioclase is approached.

In all mixtures of this system which have $CaSiO_3$ as the primary

phase, crystallization is binary in nature and remains so until pseudowollastonite is joined by plagioclase. Thenceforth the path of crystallization no longer remains in the plane of the diagram but proceeds in terms of a system of more than two components. Accordingly, the existence of a binary eutectic in this system is precluded. The point of intersection of the pseudowollastonite and plagioclase liquidus curves is not therefore an invariant point. It is very close to a composition of 89 per cent albite, and its temperature cannot be far from 1,125° C., judging from the flatness of the determined liquidus for plagioclase.

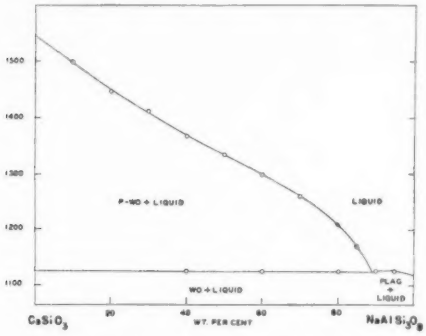

FIG. 5.—Equilibrium diagram for the system $NaAlSi_3O_8$-$CaSiO_3$.

An attempt was made, in the study of this system, to locate the wollastonite-pseudowollastonite inversion temperature. Three different mixtures were devitrified well below the inversion temperature, as a preliminary step, and these were studied thermally. At 1,122° C. these mixtures showed no pseudowollastonite present; at 1,124° C. a trace of pseudowollastonite was noted in all three mixtures; at 1,126° C. some wollastonite still persisted but had been largely transformed into pseudowollastonite. The inversion temperature was therefore assigned the value of 1,124° C. This is somewhat lower than any previously recorded temperature for this inversion. It is doubtful that this lower value could be attributed to solid solution. Recent work by E. F. Osborn[13] on the system $CaSiO_3$-$Ca_2Al_2SiO_7$ indicates a temperature of inversion which is in essential agreement with the value here found.

THE SYSTEM $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$

The results obtained from the study of this system are presented in Table 3. These results, in conjunction with the data for the three

[13] Unpublished data.

TABLE 3

THERMAL DATA FOR THE SYSTEM

$NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$

	Weight Per Cent			Time	Temperature (Centigrade)	Final Condition
	$NaAlSi_3O_8$	$CaSiO_3$	$NaAlSiO_4$			
Primary Phase Plagioclase	80.0	10.0	10.0	15 hr.	1,126°	Rare PLAG and glass
	80.0	5.0	15.0	12	1,134	PLAG and glass
				8	1,138	Glass
	70.0	11.5	18.5	8	1,110	PLAG and glass
				4	1,114	Glass
	70.0	10.0	20.0	12	1,118	PLAG and glass
				5	1,122	Glass
	70.0	5.0	25.0	3	1,126	Rare PLAG and glass
	60.0	10.0	30.0	5	1,094	PLAG and glass
				5	1,098	Glass
	60.0	6.0	34.0	5	1,088	PLAG and glass
				5	1,092	Glass
Primary Phase $CaSiO_3$	80.0	13.0	7.0	6 hr.	1,140	P-WO and glass
				10	1,142	Rare P-WO and glass
	70.0	20.0	10.0	30 min.	1,188	P-WO and glass
				30	1,192	Glass
	70.0	13.0	17.0	3 hr.	1,124	P-WO and glass
				12	1,126	Glass
	60.0	30.0	10.0	30 min.	1,249	P-WO and glass
				30	1,253	Glass
	60.0	20.0	20.0	30	1,175	P-WO and glass
				30	1,179	Glass
	60.0	13.0	27.0	12 hr.	1,106	Rare WO and glass
	50.0	15.0	35.0	5	1,110	WO and glass
				4	1,114	Glass
	50.0	12.0	38.0	10	1,084	WO and glass
				3	1,088	Glass
	40.0	50.0	10.0	30 min.	1,323	P-WO and glass
				30	1,327	Glass
	40.0	40.0	20.0	30	1,275	P-WO and glass
				30	1,279	Rare P-WO and glass
	40.0	30.0	30.0	30	1,217	Rare P-WO and glass
	40.0	20.0	40.0	30 min.	1,137	P-WO and glass
				30	1,141	Glass
	40.0	16.0	44.0	5 hr.	1,106	WO and glass
				5	1,110	Glass
	30.0	21.0	49.0	3	1,138	P-WO and glass
				3	1,142	Glass
	20.0	70.0	10.0	30 min.	1,394	P-WO and glass
				30	1,398	Glass
	20.0	60.0	20.0	30	1,344	P-WO and glass
				30	1,348	Glass
	20.0	50.0	30.0	30	1,291	P-WO and glass
				30	1,295	Rare P-WO and glass
	20.0	40.0	40.0	30	1,230	P-WO and glass
				30	1,234	Glass
	20.0	30.0	50.0	30	1,163	P-WO and glass
				30	1,167	Glass

TABLE 3—*Continued*

	Weight Per Cent			Time	Temperature (Centigrade)	Final Condition
	$NaAlSi_3O_8$	$CaSiO_3$	$NaAlSiO_4$			
Primary Phase $NaAlSiO_4$.....	60.0	4.0	36.0	24 hr.	1,126°	NE and glass
	56.0	9.0	35.0	5	1,090	NE and glass
				5	1,094	Glass
	53.0	10.0	37.0	3	1,097	NE and glass
				3	1,101	Glass
	50.0	10.0	40.0	4	1,114	NE and glass
				8	1,118	Glass
	40.0	14.0	46.0	5	1,153	NE and glass
				9	1,157	Glass
	40.0	10.0	50.0	30 min.	1,177	NE and glass
				30	1,181	Glass
	20.0	26.0	54.0	30	1,158	Rare NE and glass
	20.0	20.0	60.0	30	1,201	NE and glass
				30	1,205	Glass
	20.0	15.0	65.0	30	1,245	NE and glass
				30	1,249	Glass
	20.0	10.0	70.0	30	1,315	Rare CG and glass

limiting systems already discussed, have been employed in preparing the equilibrium diagrams shown in Figures 6 and 7. Both diagrams exhibit the boundary curves which limit the fields of the various primary phases. In Figure 6 are shown the isotherms at fifty-degree intervals. In Figure 7 the isotherms have been omitted, and arrows have been inserted to indicate the directions of decreasing temperature. In addition, the field of each primary phase has been appropriately labeled.

This system is not a true ternary system, since the field of plagioclase encroaches upon it and supplants the field which, in a true ternary system, would be that of albite. Only in that part of the system occupied by the field of pseudowollastonite, wollastonite, and carnegieite can it be said with certainty that the initial crystallization is ternary in nature. If, in addition to albite, the nepheline solid solutions contain anorthite, crystallization in this field is quaternary instead of ternary. It is at least certain that as soon as the field of plagioclase is encountered the behavior of the system becomes quaternary. Further crystallization follows a course outside of the composition triangle and must be considered in terms of the general soda-lime-alumina-silica system.

The boundary curves divide the system into five fields, namely, those of pseudowollastonite, wollastonite, plagioclase, nepheline, and carnegieite. These fields are very unequal in areal extents. An examination of the diagram with isotherms (Fig. 6) will indicate that the fusion surface of carnegieite is considerably steeper than the adjoining nepheline surface. The pseudowollastonite surface slopes more gently, passing over to the wollastonite field with apparently little change of slope. The plagioclase surface is relatively flat, with a ridge of maximum temperature extending parallel to its boundary

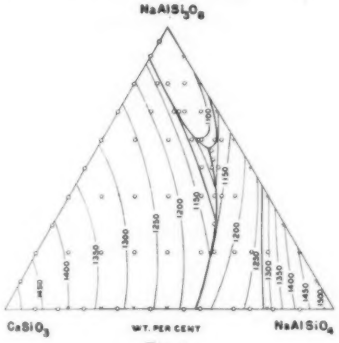

FIG. 6

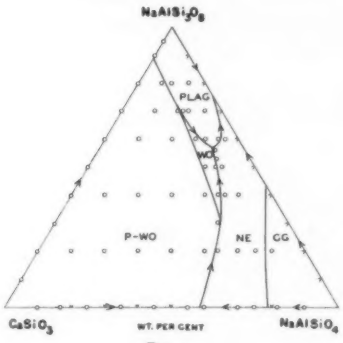

FIG. 7

FIG. 6.—Equilibrium diagram for the system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$, showing isotherms.

FIG. 7.—Equilibrium diagram for the system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$, with isotherms omitted. Arrows indicate directions of decreasing temperature.

with the two $CaSiO_3$ fields. Its steepest slope is toward the boundary curve separating it from the fusion surface of nepheline.

Even though the nepheline solid solutions may contain anorthite instead of calcium metasilicate, this tendency is probably very slight. Thus the boundary curve between the two $CaSiO_3$ fields on the one hand and that of nepheline on the other may be regarded as essentially a univariant one. The inversion curve separating the fields of pseudowollastonite and wollastonite is a univariant curve, and it is also, presumably, an isotherm. From indications obtained in the system $NaAlSi_3O_8$-$CaSiO_3$, the temperature of this curve has been established at 1,124° C. The nepheline-carnegieite boundary

curve is also a univariant one, but it is not an isotherm, since the two extremities are not points of equal temperature, one being at 1,267° C., the other at 1,280° C.

If the possibility of anorthite-bearing nepheline solid solutions be disregarded, the system has one invariant point where the fields of pseudowollastonite, wollastonite, and nepheline come together. The apparently similar point of junction of the fields of pseudowollastonite, wollastonite, and plagioclase is not an invariant one. The system possesses no ternary eutectic, since it is not a true ternary system. At first glance the point at which the fields of wollastonite, nepheline, and plagioclase meet suggests a ternary eutectic, but it is not an invariant point. On the contrary, it is a point located on the univariant curve wollastonite-nepheline-plagioclase, and marks the spot where this univariant curve passes through the plane $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$.

COURSES OF CRYSTALLIZATION

Crystallization in the system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ may be summarized as follows: All mixtures in the $CaSiO_3$ fields begin crystallization with either pseudowollastonite or wollastonite as the primary phase. As crystallization proceeds, the composition of the liquid changes directly away from the $CaSiO_3$ apex. The persistence of ternary behavior depends upon which boundary curve is first encountered. If it is the $CaSiO_3$-$NaAlSiO_4$ boundary curve, nepheline begins to crystallize as the secondary phase. $CaSiO_3$ continues to crystallize, either as pseudowollastonite or as wollastonite, depending upon whether the temperature is above or below 1,124° C. Meanwhile, the composition of the liquid follows the boundary curve until it reaches the point of junction of the wollastonite, nepheline, and plagioclase fields. As soon as plagioclase begins to crystallize, the behavior becomes quaternary. Crystallization then pursues a course outside of the $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ plane, and into that portion of the soda-lime-alumina-silica tetrahedron lying between the above-mentioned plane and the soda-lime-silica face. This behavior is a consequence of the separation from the melt of the anorthite molecule as a component of the plagioclase crystals. Mixtures lying in the plagioclase field are of course quaternary from the outset.

Those mixtures which lie in the fields of carnegieite and nepheline are initially ternary. Although the presence of the albite molecule in solid solution in the $NaAlSiO_4$ crystals somewhat complicates the course of crystallization, the path of migration remains within the plane $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ and becomes quaternary only when the field of plagioclase is encountered. In the foregoing discussion of courses of crystallization the impairment of ternary behavior by the possible presence of the anorthite molecule in the nepheline solid solutions has been considered as negligible.

PETROLOGIC SIGNIFICANCE

The system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ constitutes an internal plane in the general quaternary system soda-lime-alumina-silica, as a glance at Figure 1 will show. The present study is thus a contribution to our knowledge of one of the most important of the quaternary systems from a petrologic point of view. Some idea of the importance of a full understanding of the system soda-lime-alumina-silica may be gained from Figure 1, which shows the various mineral molecules of the system. Among these will be noted the end members of the plagioclase feldspars, the most important quantitatively of all the rock-forming minerals. A further conception of the significance of this system in petrology may be gained from the realization that the four oxides of the system constitute 90 per cent by weight of the average granite, 85 per cent of the average nepheline syenite, and 77 per cent of the average basalt. It might be mentioned in passing that the soda-lime-alumina-silica system is of great importance also in a number of technological applications. Thus a knowledge of the thermal relationships in this system is of fundamental value in the Portland cement industry, the manufacture of refractories, and in glass technology.

The study of the $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ system extends our knowledge of the stability fields of three of the mineral-forming molecules which occur in the general system. Since it constitutes an internal plane in the quaternary system, it gives information particularly concerning a portion of the interior of the tetrahedron. Much of the earlier work that has been done on the soda-lime-alumina-silica system has been restricted to the limiting faces of the

tetrahedron. Coupled with this earlier work, the present study will provide information as to how the general system will be divided into subsidiary systems and as to how the subsidiary systems will be divided into stability fields.

The present study reveals that it is impossible to crystallize pure albite in the presence of lime. It appears that if any lime is present, even if in an albite-rich melt, plagioclase rather than pure albite will be formed. Similar relations have been observed by J. F. Schairer and N. L. Bowen[14] in the system albite-diopside and by A. T. Prince[15] in the system albite-sphene. It seems necessary therefore that, in order to obtain pure albite, the lime must first have all been removed from the melt. There will be no stability field of albite within the tetrahedron, for the field of pure $NaAlSi_3O_8$ will be a planar one only, restricted to the soda-alumina-silica face of the tetrahedron.

The disparity in size of the various fields of the system herein investigated is significant in connection with the crystallization of a magma which approaches the confines of this system in its composition. For over 60 per cent of the composition range of the system, $CaSiO_3$ will be the primary phase. Mixtures lying close to the $CaSiO_3$-plagioclase boundary curve need contain only 12 or 15 per cent of $CaSiO_3$ in order to yield wollastonite as the initial phase. No igneous rocks analogous to such mixtures are known. But wollastonite is known to crystallize as an early mineral in certain instances. Thus Becker[16] states that Tornebohm observed wollastonite as inclusions in nepheline, feldspar, and aegirite. In most of its occurrences, however, $CaSiO_3$ does not seem to have been present to the extent necessary to make wollastonite the primary phase. V. Hackmann[17] describes wollastonite as an accessory mineral in the ijolite-massive of Kuusamo, Finland, to the extent of less than 4.5 per cent. As might be expected, the crystallization of nepheline and aegirite, the two quantitatively most important constituents of the rock, ap-

[14] Unpublished data. [15] Unpublished data.

[16] E. T. Allen, W. P. White, and F. E. Wright, "On Wollastonite and Pseudo-wollastonite, Polymorphic Forms of Calcium Metasilicate," *Amer. Jour. Sci.*, Vol. XXI (4th ser., 1906), p. 89.

[17] "Neue Mitteilungen Über das Ijolithmassiv in Kuusamo," *Bull. de la Commiss. Géol. de Finlande*, Vol. XI (1899), pp. 20–24.

parently began prior to that of the wollastonite. S. J. Shand[18] has noted the occurrence of wollastonite or pectolite in many of the foyaites of Sekukuniland, South Africa, some of the rocks containing as much as 6 per cent of wollastonite. But it is evidently not the first mineral to crystallize, for it occurs as grains, plates, and laths, enclosing aegirite needles and feldspar grains. In the melilite rocks of the endogenous dolerite-chalk contact zone of Scawt Hill, described by C. E. Tilley and H. F. Harwood,[19] wollastonite is interstitial to the large melilite crystals. P. G. Sohnge[20] has reported the occurrence of wollastonite as a late magmatic and early hydrothermal mineral in a pegmatite from South West Africa.

The rarity of the occurrence of wollastonite as a primary constituent of the igneous rocks is striking. The bulk of the lime content of the magma enters into the formation of the molecules of diopside, hedenbergite, tremolite, and anorthite. These molecules usually enter into solid solution with each other or with other molecules to yield more complex minerals—the pyroxenes, the amphiboles, and the plagioclase feldspars. To a lesser extent lime enters into the formation of the molecules of gehlenite, akermanite, sphene, and of various lime garnets. There is a tendency, then, for the formation of complex lime silicates, to the virtual exclusion of the simple lime silicate, wollastonite. It must be remembered that natural wollastonite is not always pure $CaSiO_3$ but rather a solid solution involving one or more of three other molecules, namely, $MgSiO_3$, $FeSiO_3$, and $MnSiO_3$. Hence it would not seem necessary that before wollastonite could form there need be a more or less complete impoverishment of the magma in MgO, FeO, and MnO or in the other oxides which enter into the composition of the complex lime silicates usually encountered. What is necessary for the formation of wollastonite is that the magma, in its crystallization, should at some time pass into or through that portion of the polycomponent system of rock-form-

[18] "The Nepheline Rocks of Sekukuniland," *Trans. Geol. Soc. South Africa*, Vol. XXIV (1921), p. 133.

[19] "The Dolerite-Chalk Contact of Scawt Hill, Co. Antrim," *Min. Mag.*, Vol. XXII (1929–31), pp. 439–68.

[20] "The Paragenesis of the Khan Pegmatite, South West Africa," *Trans. Geol. Soc. South Africa*, Vol. XLII (1939), pp. 23–24.

ing oxides in which is located the stability field of $CaSiO_3$ or of $CaSiO_3$ solid solutions. If its size in the $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ system is any indication of its size in the polycomponent system, the stability field of $CaSiO_3$ or of its solid solutions is a large one. Yet the large size of the field of a mineral is of no avail in determining the appearance of that mineral if the crystallizing magma never approaches that field. And such seems to be the situation, at least in the case of the subalkaline rocks. That crystallization of a subalkaline magma does approach this field in at least one instance in nature is suggested by the study of W. A. Deer and L. R. Wager[21] of the pyroxene of the Skaergaard intrusion of East Greenland. There is evidence that the pyroxene initially crystallized as a β-wollastonite solid solution and later inverted to a hedenbergite-clinoferrosilite pyroxene. In those rare instances in which wollastonite does occur in igneous rocks, the rocks concerned are almost invariably members of the alkaline series. In these cases, at least, crystallization must have carried the magma to the stability field of wollastonite and to that part of the field which persists at low temperatures without any such inversion as occurred in the case described from East Greenland.

The position of the nepheline-plagioclase boundary curve is of significance in the crystallization of rocks consisting largely of the minerals nepheline and albite. J. Morozewicz[22] has described just such a rock from the vicinity of the Sea of Azov, under the name mariupolite. It contains 75–87 per cent of albite and nepheline, the remainder being mainly aegirite. The nepheline content varies from 13 to 36 per cent and is in most cases less than one-half as abundant as albite. But the position of the albite-nepheline eutectic would suggest that it need only be about one-third as abundant and still be the primary phase. As might be expected, then, the porphyritic phases of the mariupolite have phenocrysts of nepheline in a matrix of plagioclase laths. Many cases might be cited to show that in those rocks in which nepheline is even moderately abundant, this mineral

[21] "Two New Pyroxenes Included in the System Clinoenstatite Clinoferrosilite, Diopside, and Hedenbergite," *Min. Mag.*, Vol. XXV (1938), pp. 15–22.

[22] "Ueber Mariupolit, ein extremes Glied der Eleolithsyenite," *Min. u. Petrog. Mittheilungen*, Vol. XXI (1902), pp. 238–46.

starts its crystallization early. When present in small amounts, however, nepheline tends to appear only interstitially as a late constituent. J. F. Williams[23] noted such a relation in the pulaskites of Magnet Cove, Arkansas, in which nepheline constitutes only about 4 per cent of the rock and occurs as interstitial grains.

The failure to encounter jadeite in the study of the $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ system supports the belief expressed by Greig and Barth[24] that jadeite is unstable under the conditions of these experimental studies and is compatible with the general belief that jadeite requires considerable pressure for its formation. Jadeite-bearing rocks, such as those described by A. Lacroix,[25] probably have formed by the interaction of albite and nepheline of nepheline syenite, and the reaction seems to have gone to completion, for the two reactants do not occur with the jadeite in the same association.

It was hoped that the system $NaAlSiO_4$-$CaSiO_3$ might provide further insight into the composition of the melilite group of minerals. The possibility was entertained that the soda content of melilites might be explained in the following way. A soda-bearing melilite molecule might be formed by the substitution of NaSi for CaAl of gehlenite, or, alternatively, by the substitution of NaAl for CaMg of akermanite. The compound derived in this manner would have the formula $NaCaAlSi_2O_7$ and would correspond to the one-to-one molar combination of $CaSiO_3$ and $NaAlSiO_4$. This possibility seems first to have been suggested by A. N. Winchell.[26] An attempt was made, as outlined in the discussion of the $NaAlSiO_4$-$CaSiO_3$ system, to find out if the molecule $NaCaAlSi_2O_7$ could be produced in a stable form. But no such compound was encountered within the liquidus range of the system. Nor were attempts to obtain indications of the existence of such a compound below the solidus attended with any greater success. These failures, however, do not conclusively dis-

[23] "The Igneous Rocks of Arkansas," *Ark. Geol. Surv. Ann. Rept. for 1890*, Vol. II (1891), pp. 39–40, 55–71.

[24] *Op. cit.*, p. 108.

[25] "La Jadéite de Birmanie: les roches qu'elle constitue ou qui l'accompagnent. Composition et origine," *Bull. de la Soc. franç. de min.*, Vol. LIII (1930), pp. 216–54.

[26] "The Composition of Melilite," *Amer. Jour. Sci.*, Vol. VIII (5th ser., 1924), pp. 375–87.

pose of the suggested theory of melilite constitution, for cases are known in which a molecule can enter into the composition of a mineral and yet does not exist as a distinct mineral.

The investigation of the system $NaAlSi_3O_8$-$CaSiO_3$-$NaAlSiO_4$ has some bearing upon the question of the origin of the alkaline rocks. One of the most widely accepted theories of alkaline rock formation is the limestone-assimilation theory proposed by R. A. Daly.[27] Reaction between the calcium carbonate of the invaded rock and albitic material of the magma is believed to have occurred, with the formation of wollastonite, nepheline, and other silicates. It is of interest in this connection that, in the investigation of the system $NaAlSiO_4$-$CaSiO_3$, some of the mixtures could, of course, have been made from albite and calcium carbonate. Those so made would have crystallized to nepheline, wollastonite, and albite (plagioclase). One of the fundamental reactions assumed to be of importance in the limestone-syntexis hypothesis would thus have been demonstrated experimentally. Such demonstration is, however, hardly necessary. The result is predictable, granting a laboratory procedure which involves heating the materials to a high temperature and maintaining them at that temperature for a period sufficient to supply all the heat necessary for the reactions and for the production of a homogeneous liquid product. Conditions in nature are never comparable with these, although a somewhat superheated natural magma might produce moderate effects of the same kind. There is in nature at least one recorded instance of clear evidence that such a reaction has taken place. Tilley and Harwood[28] describe such a case from Scawt Hill, Ireland. Here they have studied the effect of the assimilation of limestone by an olivine dolerite. The endogenous hybrid zone exhibits a transition from olivine dolerite through various stages, with the gradual elimination of pyroxene and plagioclase, until a melilite-wollastonite rock is produced. There is evidence that the nepheline was produced at the expense of the albite of the plagioclase, and that wollastonite was simultaneously formed. The progressive destruction of plagioclase with the addition of lime, result-

[27] *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill Book Co., 1933), pp. 497–544.

[28] *Op. cit.*

ing in the production of melilite and wollastonite, suggests that the anorthite of the plagioclase reacts with the calcite to yield gehlenite and wollastonite. In this same instance there is evidence that the melilite has a reaction relation toward the pyroxene, enclosing corroded crystals of the latter mineral. This relation suggests that diopside and lime may have reacted to yield the akermanite content of the melilite. Both of these reactions are found to occur in laboratory experiments with silicate melts. But it must be remembered that the decomposition of calcium carbonate in accordance with any of these suggested reactions is a strongly endothermic process. In nature there is not available the unlimited supply of heat that is at hand in the laboratory. It is difficult to say whether the slight extent to which such reactions have proceeded at Scawt Hill, as represented by the narrow hybrid zone, is indicative of the general situation. It is at least strongly suggestive of rather narrow limitations for the assimilation process, so that the ability of a magma to digest sufficient lime carbonate to produce appreciable bodies of alkaline rock is still open to question.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge his indebtedness to the members of the faculty of the department of geology and paleontology of the University of Chicago for advice and criticism and for the facilities afforded him to carry out this research project. He is particularly grateful to Dr. Norman L. Bowen, without whose constant encouragement and guidance this investigation would not have been possible. He wishes also to express his gratitude to the Catholic University of America for the Knights of Columbus and Penfield fellowships granted to him by that institution to finance this project.

WIND-CUT STONES IN KANSAN DRIFT OF WISCONSIN[1]

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ABSTRACT

Many stones in a supposed Kansan terminal moraine near Stevens Point, Wisconsin, appear to be ventifacts. Some of them show also varying degrees of wear during glaciofluvial transport following the sandblasting. The position of many of the ventifacts beneath undisturbed pseudostratification indicates that the wind-scouring preceded incorporation in the till. The probability that the wind-scour occurred during advance of the Kansan ice is discussed.

INTRODUCTION

Stones whose surface character or shape have been modified through abrasion by wind-driven sand are common in modern deserts and in many consolidated eolian deposits or fossil deserts. These range in age from pre-Cambrian to Recent. K. Bryan[2] proposed that such wind-etched, wind-scoured and polished, and wind-shaped stones be classified, as will be done in this paper, under the general term "ventifact." W. H. Hobbs[3] found many of them on the surface of outwash plains and valley trains peripheral to the Greenland ice-cap. Violent anticyclonic winds coming off the ice find an ample supply of sand and silt on these barren periglacial borders and drive it against and across stones too large for them to pick up. Ventifacts have also been found in abundance within and upon modern glacial deposits and those of the late Pleistocene in many parts of the world. Bryan[4] cites numerous examples on the glaciated plains of northern

[1] Presented at meetings of the Wisconsin Academy of Sciences, Arts and Letters, April 4, 1941.

[2] "Wind-Worn Stones or Ventifacts—a Discussion and Bibliography," *Rept. Committee on Sedimentation for 1929–30, Natl. Res. Coun. Circ. No. 98* (1931), pp. 29–50.

[3] "Loess, Pebble Bands, and Boulders from Glacial Outwash of the Greenland Continental Glacier," *Jour. Geol.*, Vol. XXXIX (1931), pp. 381–85.

[4] *Op. cit.*

Europe. J. B. Woodworth and others,[5] Bryan,[6] N. S. Shaler,[7] the senior author of this paper,[8] and others have described a profusion of ventifacts in southeastern Massachusetts and Cape Cod. F. E. Matthes[9] dug many out of glaciofluvial gravels on Nantucket that have not been disturbed since they were deposited and concluded that these were formed during advance of the Wisconsin ice sheet.

Although the glacial deposits of the Middle West have received a great deal of study, there are surprisingly few references to ventifacts associated with them. A survey of ventifact localities in the United States made by C. K. Wentworth and R. T. Dickey[10] lists only four sources of wind-cut stones in Wisconsin. At two of these the stones occur in Upper Cambrian sandstone, while at the other two they are associated with late Pleistocene or Recent deposits. There are, likewise, few references to ventifacts formed during pre-Wisconsin stages of the Pleistocene in the glaciated portions of the world. W. C. Alden and M. M. Leighton[11] found some in a pebble band at the top of the Iowan till, and G. F. Kay[12] later concluded that these had been formed during retreat of the Iowan ice before deposition of the Peorian loess that lies above them. Matthes reports[13] that Alden showed him a "clean-cut ventifact which he found some years ago in material dug from the Hennepin Canal, to the east of Geneseo, Illinois" in what is presumably outwash of early Wisconsin age. Inasmuch as the pebble is of limestone and is well-

[5] "Geography and Geology of the Region Including Cape Cod, the Elizabeth Islands, Nantucket, Martha's Vineyard, No Man's Land, and Block Island," *Mem. Mus. Comp. Zoölogy, Harvard College*, Vol. LII (1934).

[6] "New Criteria Applied to the Glacial Geology of Southeastern Massachusetts," (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XLIV (1932), p. 176.

[7] "The Geology of Nantucket," *U.S. Geol. Surv. Bull. 53* (1889), pp. 21–26 and Pl. X.

[8] L. R. Thiesmeyer *et al.*, "Late Glacial Ventifacts of Cape Cod" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 1939.

[9] "Wind-faceted Pebbles from the Glacial Drift of Nantucket," *Jour. Wash. Acad. Sci.*, Vol. XXIV (1934), pp. 195–96.

[10] "Ventifact Localities in the United States," *Jour. Geol.*, Vol. LXIII (1935), pp. 97–104.

[11] "The Iowan Drift," *Iowa Geol. Surv.*, Vol. XXVI (1917), pp. 152–53, Fig. 13.

[12] "The Origin of the Pebble Band on Iowan Till," *Jour. Geol.*, Vol. XXXIX (1931), pp. 377–80.

[13] Personal communication.

preserved, Matthes concludes that "it is probably not older than Wisconsin."

During a field trip in November, 1940, the junior author recognized prominent fluting on a boulder of granite gneiss in Kansan[14] till of Wisconsin as evidence of wind abrasion, even though weathering had obliterated the polish and smoothness generally characteristic of wind-scoured stones. Immediate search by the senior author and a class of a dozen students proved fruitful. In half an hour fifty-two well-formed ventifacts were collected and scores of weathered or doubtful ones discarded. A subsequent visit to the same locality during the winter yielded about sixty more, and a second locality rich in ventifacts was found. Since most of the ventifacts were dug directly out of the till they must be at least as old as Kansan. To the writers' knowledge they are, therefore, not only the first to be reported from drift of that age in this country, but also the first to be found deeply embedded in glacial till of the Middle West. This paper aims to describe the occurrence and characteristics of these ventifacts and to urge other workers to seek them in glacial deposits of the same age elsewhere.

GEOLOGIC OCCURRENCE OF THE VENTIFACTS

LOCATION

The wind-cut stones described in this report were first encountered in a roadside pit on the north side of State Highway 54 about six miles southeast of Stevens Point and one mile west of Maynard's Corner,[15] the intersection of Highway 54 with County Trunk Highway J (Fig. 1). The pit is excavated in sandy and bouldery till just east of the crest of a low terminal moraine at the edge of the driftless area. This moraine extends for about twenty miles across a re-entrant between minor lobes of the Wisconsin terminal moraine which overlap it on north and south. S. Weidman[16] named this the "Arnott" moraine and correlated it with the Marshfield-Nielsville mo-

[14] This age designation is taken from S. Weidman's "The Geology of North Central Wisconsin," *Wis. Geol. and Nat. Hist. Surv., Bull. 16* (1907), pp. 456–66. The writers have corroborated only part of his evidence.

[15] Also known locally as Webb's or Fletcher's Corner.

[16] *Op. cit.*, p. 456.

raine. He assigned it to the Kansan stage of glaciation because of the deeply weathered character of its constituents, its position beneath the Wisconsin deposits, and the erosional modification of its topography. A second pit yielding abundant ventifacts was found in a similar position on the moraine about a quarter of a mile north of the

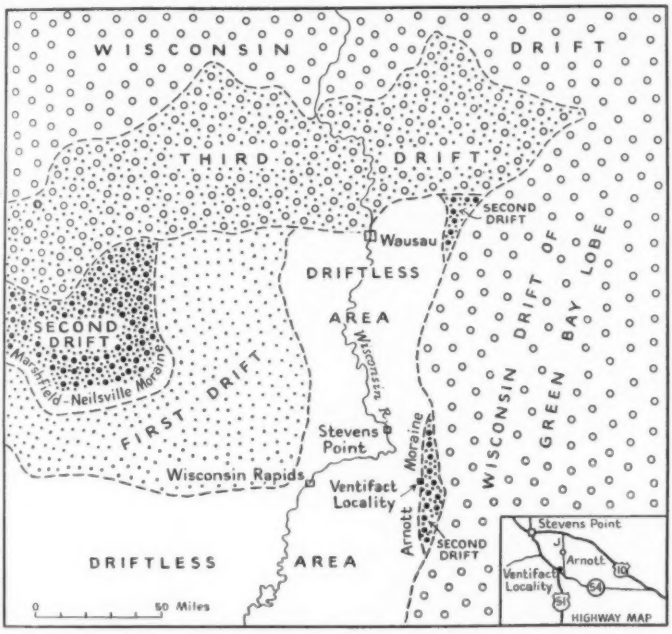

FIG. 1.—Sketch map of drift sheets and ventifact locality in north-central Wisconsin. (After Weidman.)

first one, alongside a gravel road leading east from the intersection of Highway 54 with U.S. Highway 51 (Fig. 1).

CHARACTER OF THE DEPOSIT

The till at these localities is very sandy. It contains local irregular patches of fine sand and silt that exhibit pseudostratification. It is a typical heterogeneous accumulation of subangular stones and boulders (Fig. 2), some of which show excellent glacial striae. The boul-

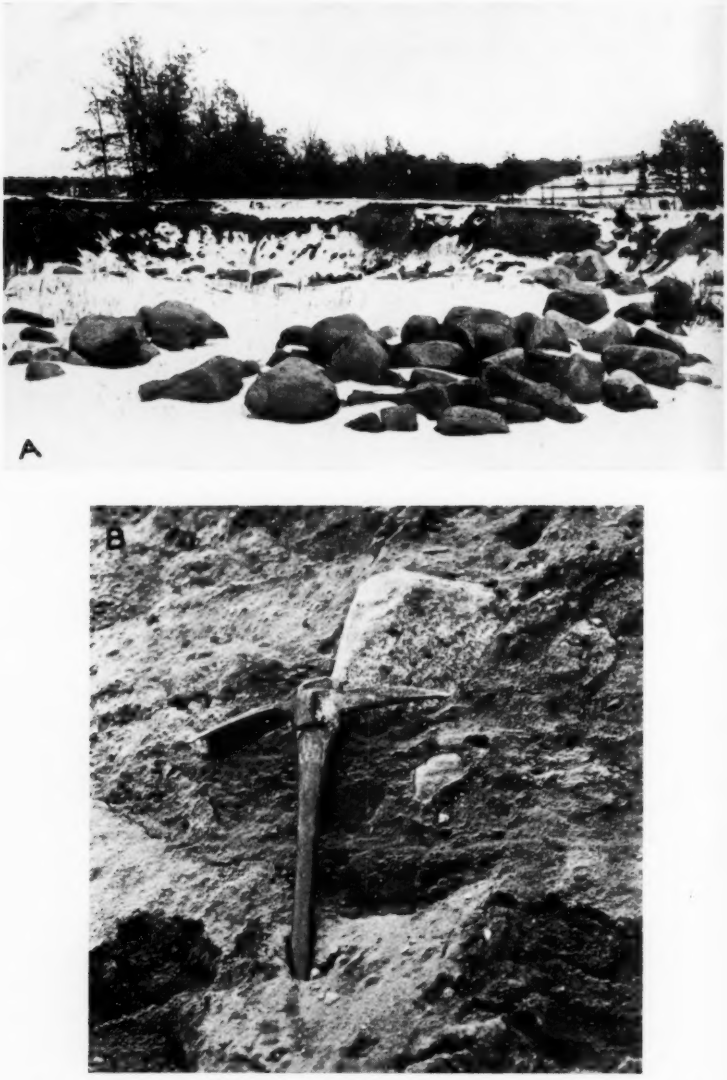

FIG. 2.—Till of the Arnott Moraine—*A*, pit on Highway 54 near crest of the moraine; *B*, sandy till of the moraine. (Photos by W. P. Gilbert.)

ders range in size up to 10 feet in diameter and are chiefly of coarse, granitic rock types. Granites, gneisses, and quartzites predominate among the smaller stones. The matrix consists largely of quartz sand and shows no effervescence. Strong and deep weathering of the till is indicated by its deep red to chocolate and rusty brown color down to a depth of at least 10–12 feet beneath the surface and is even more apparent in the complete disintegration of many of the boulders to heavily kaolinized gruss. Subangular boulders of granite in place 6 or 8 feet below the surface retain their outline but crumble to sand easily when struck with a hammer. This indicates prolonged and deep penetration of weathering agents and serves to corroborate in part Weidman's conclusion that this drift belongs to an early part of the Pleistocene.

POSITION OF THE VENTIFACTS

The ventifacts lie embedded in the till at various depths and with random orientation of their wind-scoured surfaces. Many of them were found in slumped material on the walls of the pit and a few on the surface above the pit. The latter were probably brought to the surface by erosion of the till or by overturning of its upper zone due to frost, plant roots, etc. Even with snow blanketing the bottom of the pit and, presumably, covering some of the best ventifacts loosened by slumping and made more conspicuous by rainwash, nearly a hundred good ones were collected in a few hours of digging into the pit walls, and several hundred poorly developed or doubtful ones were found.

DESCRIPTION OF THE VENTIFACTS

SIZE

The wind-cut stones found thus far show a range in size from pebbles $1\frac{1}{2}$ inches to a boulder $2\frac{1}{2}$ feet in diameter. Experience of the senior author with similar stones in southeastern Massachusetts shows that pebbles only $\frac{1}{4}$ inch in diameter may have wind-cut facets and polish. This is in contrast to the conclusion of Wentworth and Dickey[17] that only pebbles greater than $\frac{1}{2}$ inch are "sufficiently stable to be carved to distinct shapes." It is expected, moreover, that further search will disclose both smaller and larger ventifacts in the Arnott moraine.

[17] *Op. cit.*, p. 103.

LITHOLOGIC TYPES

At least a dozen types of rock are represented in the collection, including quartz, quartzite, chert, chert-pebble conglomerate, fine-grained gneiss, coarse granite and gneiss, greenstone, schists, feldspar porphyries, rhyolite, and iron formation. As might be expected, siliceous types predominate and show the best preservation of the sandblasted features. Feldspathic rocks in the collection are so dulled and pitted by weathering that much of the evidence of wind abrasion is indistinct and could easily be overlooked by the untrained observer.

SHAPES

Many of the shapes characteristic of wind-sculptured stones have been found among these Wisconsin ventifacts, including (see Figs. 3 and 4):

1. Einkanter—single smooth facets cut across subangular and rounded cobbles.
2. Zweikanter—ridge-shaped stones with two opposing facets meeting along a more or less serrate interfacet edge.
3. Dreikanter—pyramidal-shaped stones with three facets meeting in a common, angular apex.
4. Pyramidal and polygonal—more than three facets.
5. Triquetrous—brazil-nut shape with three facets meeting at approximately 60°.
6. Irregular—partially developed facets, with pits, flutings, serrate edges, and cuspate hollows; these represent stones of irregular shape (because of solution and weathering) only slightly modified by wind action.

Contrary to the impression given in some textbooks, dreikanter are the exception rather than the rule among these wind-scoured stones.

FEATURES INDICATIVE OF WIND ABRASION

The features described below and shown by the stones considered in this paper may be seen on rocks subjected to sandblasting on modern deserts and beaches. Such phenomena have all been ascribed by various writers to eolian abrasion and are difficult to explain except as products of wind action. Since these features may serve, therefore, as useful criteria for recognizing ventifacts, it seems appropriate to list and discuss them here.

1. *Polish.*—This varies from a dull gloss to patches of brilliant, cellophane-like luster like that on quartz ventifacts from modern deserts. The polish is generally well preserved only on quartz or

quartzite ventifacts and on quartz grains in rocks of granitic composition. On some of the stones the polish has been dulled by weathering, indicated in hydration of feldspar grains on wind-cut facets. On others it has been largely removed by abrasion during glaciofluvial or glacial transport, as is evidenced by rounded and minutely

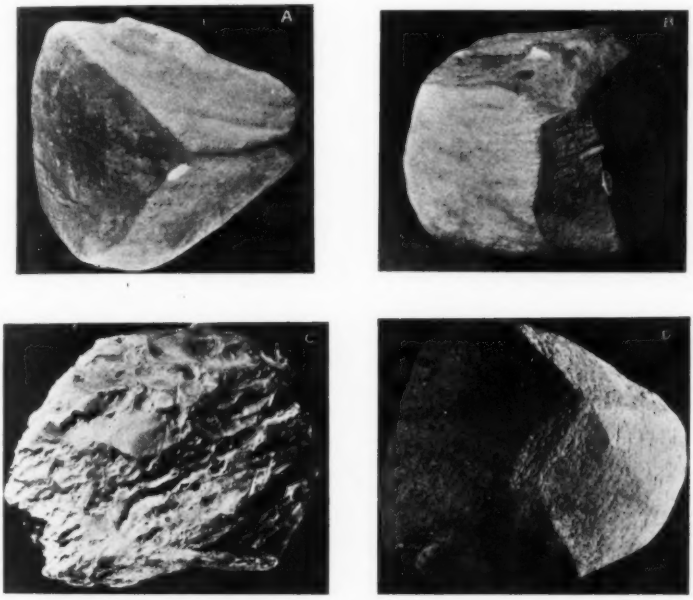

FIG. 3.—Shapes of the ventifacts: *A*, pyramidal quartzite cobble; *B*, polygonal quartzite cobble; *C*, deep pits and flutings on chert conglomerate; *D*, polygonal granite ventifact. (Photos by W. P. Gilbert.)

pitted interfacet edges. On still others it may never have existed because the abrasive was too coarse, as was suggested by Matthes.[18] Production of a polish, probably by the silt and dust rather than by the sand in a wind-stream, seems to be the first step in modification of rock surfaces. Stones that show very little shaping and excavation and portions of good ventifacts that have been only slightly smoothed nevertheless show moderate to high gloss.

[18] *Op. cit.*

2. *Smooth surfaces.*—These may be so smooth and lustrous that they feel distinctly greasy; or they may be partially pitted where weathering or abrasion by some other agency subsequent to the sandblasting has begun to destroy the polish.

3. *Wind-smoothed faces and wind-cut facets.*—Where these bevel a rounded pebble, cobble, or boulder and make it flat or pyramidal on only one side, it seems clear that they were actually cut by the sand

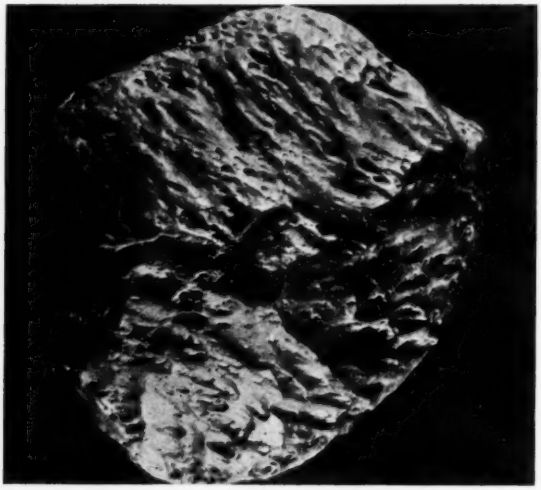

FIG. 4.—Fluting and pits diagonal to facet edges. (Photos by W. P. Gilbert)

and much material has been removed. On polygonal blocks, however, it is entirely possible that the smooth surfaces or facets represent merely minor modification of original fracture surfaces (joints). Those facets that can reasonably be ascribed to wind-cutting alone are generally concave upward and many of them bear small shallow cusps that meet in sharp ridgelike edges. Many of the facets exhibit what Matthes[19] calls "the distinctive feature of all wind-cut facets" in having a sharp terminal edge on their leeward margins but a rounded or grooved and highly polished surface on their windward borders.

[19] *Ibid.*, p. 195.

4. *Differential etching.*—Phenocrysts, pebbles in sandstones, veins, etc., may be etched out or may stand in relief because of their differential resistance to abrasion (Fig. 4). These are easily distinguished from pits and prominences produced through weathering, however, because they are so smooth and are more or less polished. Some of the irregularity may have been already present as a weathering phenomenon when the sandblasting began and has been only slightly modified.

5. *Fluted surfaces.*—These consist of subparallel, discontinuous, shallow grooves. Their bottoms are smooth and polished and edges between them are sharp. The hollows deepen to leeward and may terminate in deep pits with overhanging rims. The long dimension of these furrows is generally parallel to the wind direction, and their orientation commonly is entirely independent of pre-existing structures in the rock. (Grooves formed by differential solution generally follow the less resistant elements of such structures.) Flutings on one boulder of granite gneiss from the Arnott moraine cut diagonally across its foliation. This is to be expected because of random orientation of gneissic structure in stones on a wind-swept surface. The fact that fluting is not common on hard rocks of homogeneous texture suggests that its development is, however, initiated and controlled somewhat by less resistant parts of the rock.

The fluting may be diagonal to interfacet edges, and flutings on adjacent facets may be oriented quite differently (Fig. 4). Such ventifacts show that opposing facets could not have developed on them simultaneously by winds from a single direction, as has been suggested for certain ventifacts by some writers. The wind direction was not, furthermore, essentially perpendicular to the strike of the facet surface; and it is probable that the stone rotated into a new position between the carving of one facet and that of the adjacent one.

6. *Pits and cuspate hollows.*—These are smooth, greasy, and lustrous. Their size and distribution is controlled by the size and distribution of nonresistant units in the rock. They are common on porphyry, conglomerate, breccia, amygdaloid, and granite. Some of the hollows were probably already present as depressions when the

wind abrasion began, and they have been merely smoothed. This seems especially true of those cobbles that have smoothed pits nearly an inch deep (Fig. 3, *C*).

Abundant shallow cusps on the facets of quartz, quartzite, and chert probably represent minor modification of the pronounced conchoidal fracture surfaces characteristic of such rocks.

ABRASION FOLLOWING WIND SCOURING

Scores of ventifacts that had clearly suffered abrasion by some other agency after the sandblasting have been found in the Arnott moraine. Many others whose sand-etched surfaces had been almost obliterated by such action were probably overlooked, or were discarded because of inconclusive evidence of previous wind action. In this subsequent abrasion, interfacet edges and sharp ridges between adjacent shallow flutings were rounded. The greasy smoothness and high polish generally characteristic of wind-swept surfaces were decidedly reduced or totally removed from areas contiguous with such roundness. Instead, the surface at these places has a far less lustrous and minutely pitted smoothness that is commonly somewhat harsh to the touch and is usually attributed to abrasion during transport by water or ice. Yet on parts of the same specimens, especially in concave hollows, the wind-developed smoothness and polish are still well preserved. All semblance of a ventifact shape (facets, pyramidal outlines, etc.) was destroyed on some stones leaving only the parallel flutings, furrows, and elongated pits whose polished concavities could only be products of eolian sandblasting.

Such modifications of wind-sculptured surfaces *could* have occurred during transport by the ice which brought these stones to their position in the moraine. If so, we have difficulty in explaining the remarkable fact that not a single ventifact has yet been found with glacial striae across its wind-carved facets. The methods of incorporation in advancing ice and transport *without* notable abrasion are not clearly understood, but many examples of ventifacts in till are now known in which this must have occurred. That so many of the Wisconsin stones escaped posteolian abrasion so completely suggests that the ventifacts had already been abraded to varying de-

grees before the ice moved them into the moraine and that they were affected very little during this transfer.

Many stones that were wind-carved as they lay on an outwash plain in front of an advancing glacier might be moved by shifting channels of melt water. The amount of wear on each stone would vary with such factors as distance of transport, size, and lithology of both stone and abrasive, speed of current, etc. Some would be little altered; others would have all evidence of former wind abrasion destroyed. When the ice advanced across the glaciofluvial terrain it would pick up stones showing varying degrees of stream wear superimposed on their wind-cut features and scramble them all into the same mass of till. K. F. Mather and others[20] have found thousands of such stones in the glaciofluvial gravels of Cape Cod which must have had essentially that history. It seems wholly plausible that these water-worn ventifacts of Wisconsin originated under very similar conditions.

WEATHERING

Most of the ventifacts considered in this paper show considerable weathering, both those that escaped abrasion after wind-polishing and those that did not. That there has not been even more weathering in so porous a matrix is surprising. As might be anticipated, the amount of weathering is least on chert and quartz-rich rocks and greatest on coarse granites and mafic rocks. Although all these stones have preserved excellently other shapes and features characteristic of wind-cut surfaces, the polish and smoothness of the feldspathic and mafic ones are dulled by deep hydration and by solution pitting. The sharpness of flutings and facet edges has not been appreciably reduced by the weathering on some specimens even though kaolinization of the feldspars may have penetrated nearly an inch beneath their wind-scoured surface. Here and there on the weathered stones a small patch of polish and fluting that somehow escaped hydration remains as clear evidence of the former wind-sculpturing—but an evidence that may only be discovered through careful examination of the stone.

[20] "A Preliminary Report on the Geology of Western Cape Cod, Massachusetts," *U.S. Geol. Surv. and Commonwealth of Mass. Co-operative Project, Bull. 2* (1941), pp. 15–16 and Fig. 4.

AGE OF THE VENTIFACTS

The writers of this paper believe that these wind-cut stones, embedded so deeply in till, were shaped before the till was deposited and were picked up in the final surge of the ice to its terminal position. Other possibilities are, however, considered in the following discussion.

Bryan[21] postulated that the Cape Cod ventifacts were formed at the surface during recession of the ice and were then churned down into subjacent till or outwash deposits by vigorous frost action in a periglacial climate. Matthes[22] found ventifacts in outwash gravels beneath the topmost till on Nantucket Island and concluded that they were produced during advance of the late Wisconsin ice. The senior author of this paper and his colleagues[23] found wind-cut stones both in undisturbed outwash and in till of Cape Cod, well below the thin (18 in.–3 ft.) surficial zone of disturbance that is conceivably attributable in part to frost action. These writers presented evidence to show, furthermore, that ventifacts may be produced both during advancing and retreating phases of ice-lobe activity and that those on Cape Cod were formed before all the ice of the last advance had disappeared from the region. It appears, therefore, that the mechanism advocated by Bryan[24] is not necessary to explain the presence of ventifacts embedded deeply beneath the surface with random orientation of wind-cut features. It can apply only where evidence of overturning is found in the matrix of the deposit.

Despite the probable early Pleistocene age of the Arnott moraine and repeated opportunities for vigorous frost action on its exposed surfaces during succeeding stages of the ice age, no evidence of deep overturning could be found. On the contrary, lenticular streaks of fine silt and sand that form pseudostratification in the till lie undisturbed within 6 feet of the surface. Some ventifacts were dug out of the till several feet below such streaks. These stones must, therefore, have been carved before advance of the ice to its terminal position in the moraine.

[21] "New Criteria Applied . . . . ," *op. cit.*

[22] *Op. cit.*, p. 196.

[23] *Op. cit.*, p. 1939.

[24] "New Criteria Applied . . . . ," *op. cit.*

It is not impossible, of course, that some ventifacts lying above these streaks could have been formed at the surface and then churned down into the till. If so, one would expect them to show better preservation of wind-cut features than those below; but no such distinction could be found among the stones from the Wisconsin localities. Consequently, the writers favor the view that, with the possible exception of those in the upper few feet of material, all these ventifacts were produced during the same substage of the Pleistocene and are lying in the till today essentially in the positions they took when deposited.

The Kansan age of this till was predicated by Weidman[25] on the following evidence, and observations of the writers corroborate part of it.

1. The Arnott moraine is pre-Wisconsin because the Wisconsin drift border overlaps it on north and south.
2. It is early Pleistocene as shown by the degree of weathering of the till itself and of its boulders, and a greater modification of its topography than is seen on Illinoian or Iowan deposits.
3. It is correlated with the Neilsville moraine on the basis of lithology, degree of weathering, and topographic maturity. The Neilsville moraine in north-central Wisconsin is overlapped by a moraine assigned to the third drift (Illinoian) which is clearly much younger lithologically and topographically. The Neilsville is regarded, therefore, as Kansan in age; and it follows that the Arnott moraine must likewise be Kansan.

It seems unlikely that the wind-worn stones could have been formed in early Kansan or pre-Kansan time, could have survived both long weathering during the Aftonian interglacial episode and transport during advance of the Kansan ice sheet, and still retain so beautifully their wind polish, delicately etched surfaces, and sharp facet borders, especially on rocks so susceptible to weathering as granite. Evidence that they are not post-Kansan has been detailed above. The writers believe, therefore, that they were sand swept on outwash plains in front of the advancing Kansan ice sheet. Then they were moved forward, probably only short distances in its final advance, and deposited in the till of the Arnott moraine along with many stones that had escaped wind scour. Some of them were no doubt carried short distances by melt water in shifting channels on

[25] *Op. cit.*

the outwash deposits and thereby lost parts of their wind-cut features before the ice itself moved them to their present positions. Some may have been modified by abrasion during the glacial transport. All were subjected to prolonged weathering as the till surrounding them underwent decomposition. Those that lie at and near the surface today probably reached that position through erosion of the overlying material, some surficial frost action, and overturning by plant roots, etc.

SUMMARY AND CONCLUSIONS

Wind-cut stones of varied size and lithologic type have been found at localities in a supposed Kansan terminal moraine near Stevens Point, Wisconsin. They are embedded with varying orientation of their wind-scoured surfaces in deeply weathered sandy till, some of them lying below undisturbed structures of the drift. Preservation of features formed by eolian abrasion is best on highly siliceous types. Most of the stones show marked weathering, and many of them were abraded by some other agency after the wind scouring. It is suggested that this was stream wear on outwash deposits in front of advancing Kansan ice. The ventifacts were probably formed during the Kansan glacial stage under conditions similar to those which produced a profusion of wind-cut stones and boulders during later stages of the Pleistocene elsewhere. It is anticipated that further search will disclose many more of these stones, not only in the Kansan moraines but in other drift deposits of the central states.

ACKNOWLEDGMENTS.—The writers are happy to acknowledge their indebtedness to Professor Kirk Bryan of Harvard University who unwittingly stimulated search for ventifacts in the drift sheets of the Middle West by his insistence that they should occur in abundance in that region, and to Professor Paul Gilbert of Lawrence College for considerable aid in the preparation of illustrations for this paper.

COMPRESSION CREEP OF RUBBER AND ROCK

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ABSTRACT

A compressible solid may overcome resistance to its bodily movement by a piecemeal operation if the mass involved has dimensions permitting sufficient linear compression. Because resistance, such as friction, may be overcome locally and in successive stages, a small fraction of the force needed for an immediate effect will, given enough time, bring about the same bodily movement. This slow kind of movement against outside resistance, named "compression creep," suggests the view that the rate of geological deformation is correlated better with small forces operating through long time, than with mighty forces in critical periods. A laboratory demonstration of the principle is made possible by the use of rubber sheets. Since this material has notable compressibility from forces needed to overcome friction, it serves admirably as a model of a great rock sheet. Application of the principle of compression creep is made to problems involved with the overcoming of friction along the soles of overthrusts, with the rate and periodicity of mountain folding, and with the deformation of the earth by the weight of ice sheets.

INTRODUCTION

A solid, when subjected to forces causing notable linear compression, may overcome resistance to its bodily motion by a piecemeal operation. For example, if pressure is exerted on the end of a long slab of compressible solid, which lies conformably on a horizontal surface of uniform friction, it is not expected that friction is overcome at the same instant under all parts of the slab. The predictable effect is rather that linear compression is registered first at the end where pressure is applied, and that friction must be overcome first under this end, and successively in all intermediate areas, before compression and consequent movement can be effected at the distant end. In theory, therefore, a solid with linear compressibility can be made to move slowly and bodily against opposing forces by pressures small compared with the total resistance. This process, in which a small force in long time produces the same effects that call for a larger force in short time, will be referred to as "compression creep." By qualifying the process in this manner, no confusion will arise with the pre-empted name "creep," the resistance to which is internal, whereas compression creep implies external resistance.

An attempt to demonstrate compression creep in the laboratory by using a small slab of rock opposed by friction would be frustrated by the minute amount of compression caused by the force needed to overcome friction. A smaller force conceivably might cause an immeasurably slow compression creep—so slow, in fact, that the rock slab would behave in experiment essentially as an incompressible solid. This statement, however, does not apply to rock bodies of great length. Slabs on the scale of great overthrust sheets would show linear compressions amounting to tens and even hundreds of feet from forces small compared with those needed for a momentary overcoming of friction. Such sheets are expected to overcome this friction piecemeal and to submit, therefore, to compression creep.

To permit a simple laboratory demonstration of compression creep it is necessary to find a solid with pronounced linear compressibility. Rubber sheets serve the purpose well, and a series of experiments on these will be used to illustrate the principle that a small force operating through long time can produce effects calling for a much greater force in short time. This principle has obvious and important bearings on geological processes, and some of these will be discussed. Deformational effects are profound in the lithosphere, and earth movements are slow. These facts, if related, as they appear to be, suffice in themselves to suggest the likelihood of a similar relation between small forces and long time. The principle of compression creep confirms this probability.

EXPERIMENTS SHOWING COMPRESSION CREEP OF RUBBER

A sheet of sponge rubber, 2 feet square and $\frac{1}{2}$ inch thick, and weighing about $5\frac{1}{2}$ pounds, was laid on a horizontal surface of glass. By means of pulleys, strings, and scale pans, pressure was exerted uniformly on one end of the sheet through the straight edge of a rectangular frame which rested on rollers to avoid friction. A long series of repeated tests showed that the same force caused different rates of movement on different days. The explanation of this variation probably lies in changes of atmospheric pressure, temperature and humidity. The series of results to be recorded were derived, however, during times so brief that these changes would likely be in-

considerable. Measurements indicated that a linear compression of 1 part in about 800 was produced in the sheet by a 1-pound weight.

In one series of measurements on a single rubber sheet, 14 pounds directed against one end of the sheet caused a fairly rapid bodily motion, but with no apparent acceleration of rate. It was concluded that this force represents as close an estimate of the friction of the sheet as could be made by this method, but what might be termed the "total friction" is probably larger. A force of 12 pounds caused a constant rate of 1 inch in $1\frac{1}{2}$ minutes. Successively: 10 pounds changed the rate to 1 inch in 4 minutes; 8 pounds to 1 inch in 16 minutes; and 6 pounds to 1 inch in about 100 minutes. Movement was caused by smaller forces, but disturbing factors lessen the value of a reading at this end of a series. In the series under description, a small displacement was noted at the end of 24 hours from a force of 4 pounds. The conclusion permitted by this and similar series is that, through compression creep, one-fourth or less of the force represented by total friction will cause a slow, bodily migration of the sheet. In other words, when compressible material is involved, a small force, given enough time, may produce effects which seem to call for a "mighty" force in common geological parlance.

Another series of measurements was made to determine the effects of an uneven distribution of resistance (friction) on the rate of compression creep. Using the same force in both instances, the rate of a sheet carrying a column of circular weights of 3-inch diameter was compared with that of the same sheet carrying the same load in the form of a second rubber sheet resting conformably on its surface. The rates were found to be essentially the same; actually, the measured rate was slightly faster when the column of weights was used. This effect shows clearly that compression energy can be stored from a small force in the entire sheet and may then be called into play to overcome excessive local resistance.

COMPRESSION CREEP IN ROCK

Theoretically, a slab of rock with dimensions similar to the rubber sheet should show some of the same compression creep against friction. However, the enormity of the time factor alone would defeat a demonstration owing to the slight linear compressibility of rock.

The rubber sheet, nonetheless, serves as an excellent model for rock of great dimension; it permits a qualitative demonstration of the principle involved; and the scale is quantitatively close enough to permit geological comparisons. A large enough sheet of rock, when subjected to linear compression and encountered by resistances, should show a large measure of the flexibility of the rubber sheet when forces commensurate with the sizes of the respective sheets are used. Up to the limit of strength, as commonly measured, rock is estimated to have a linear compressibility of 1 part in 800 to 1,000. Accordingly, in an overthrust sheet acted upon by pressure directed at the roots, say 200 miles from the front, a linear compression of 1,000 feet is expected before rupture would ensue. Only one-tenth of this force would provide a shortening of at least 100 feet, an amount which appears more than ample to require a piecemeal overcoming of friction along the sole, and, accordingly, to permit the operation of compression creep.

The phenomenon of creep in solids has been demonstrated by C. E. VanOrstrand[1] in a steel tape under tension and by David Griggs[2] in other solids by linear compression of small specimens. In these experiments the linear contraction and elongation were registered only against resistance within the specimen, so that compression creep, which implies the overcoming of outside resistance, was not involved in the deformations. If pressure were exerted on a small area of the surface of a large mass of rock, the resulting deformation would embrace both kinds of creep. The creep caused by the linear compression of a free cylinder of rock involves all parts of the cylinder at the same time, while in the latter instance, this kind of creep must wait for compression-creep effects nearer the surface before it visits greater depths. Obviously, elastic equilibrium would be approached more slowly when compression creep is involved. Moreover, the increased importance of the time factor is associated with the linear and other dimensions of the mass undergoing deformation. That is to say, the same approach to elastic equilibrium will require more time in a large than in a small mass. The bearing of this con-

[1] "Notes on Isostasy," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), pp. 300–305.

[2] "Creep of Rocks," *Jour. Geol.*, Vol. XLVII (1939), pp. 225–51.

clusion is apparent on the problem of the elastic deformation and recovery of the earth, resulting from the accumulation and melting of ice sheets.

Whenever and wherever rock masses on a large scale are being deformed, compression creep is bound to be a considerable factor. Resistances to be overcome by one mass with respect to another may be by fracture, by plastic or recrystallization flow, or by the setting-up of recoverable strain. It is not unlikely that, with great development of frictional heat, rock might melt in some stages of compression creep, particularly when extreme local resistance is overcome relatively quickly, but the general slowness of movement opposes the local retention of heat long enough to permit melting. At great depth the possibility of melting is more likely to be realized. It would seem possible, having in mind the general association of intrusion and deformation, that the sole of a great overthrust might pass normally into a sheet of magma.

Although compression creep has a broad bearing on all geological deformation, it lends itself particularly well to an explanation of the movement of great overthrust sheets against enormous resistance, without their structural collapse. The concept has a bearing, as well, on the question of the rate and periodicity of mountain folding, particularly as these are viewed in the thermal-contraction theory. These applications will be briefly discussed, together with the relation of the principle to the time and mass factors involved with deformation of the earth by ice sheets. Other possible applications are numerous, such as to the mechanics of flow of ice and rock salt in large masses, but will not be discussed at this time.

One further aspect of compression creep should be kept in mind, owing to its bearing on regional and intensive deformation and less directly on metamorphism. It comes from the fact that intense local deformation may arise from the energy of compression stored in a mass of great regional dimension—an earthquake of small focal area in a much larger fault zone may be an example. Much of the regional mass may be similarly affected, not all at once, but successively in different parts, to give the impression of mighty regional forces, whereas the total effect may imply, instead, the importance of the

time factor. It may be recalled that the rubber sheet traveled as readily when a weight was concentrated on a small area of its surface as when the same weight was evenly distributed.

OVERTHRUSTING AGAINST FRICTION

The amount of linear compression possible from different forces acting upon an overthrust sheet, 200 miles from front to roots, has been indicated. With a force only one-tenth that required for the structural collapse of the sheet, a compression of 100 feet or more seems probable. Friction along the sole resists linear contraction at the rear, where the compressive force is being applied. When the friction under the first few miles is overcome the wave of compression can advance into new areas, there to attack and to overcome new friction. Slow movement of the entire sheet is accordingly effected by a force which may be a small fraction of that represented by total friction. Should friction not be uniformly distributed along the sole, accumulated energy of compression in the entire sheet may operate locally to overcome excessive resistance. Successive operations of this nature eventually permit the migration of the whole sheet.

Objection has been made to the view that low-angle reverse faults of great dimension are produced by overthrusting, notably by advocates of tectonic hypotheses which favor underthrusting connected with the plunging of portions of the crust into a hypothetical weak substratum. The basis for this dissent is that the magnitude of friction along the sole would lead to collapse of the sheet when great distances are involved. This objection was concisely framed by A. C. Lawson:

> As to the unreality of positive overthrusting I have elsewhere shown, from a theoretical point of view, that in major thrusts the upper block is incapable of propagating for great distances the stress necessary for translation against friction, and this conclusion is sustained by observation.[3]

This statement carries little weight in the light of the principle of compression creep. Furthermore, the evidence that many overthrust sheets are deformed does not justify the conclusion that

[3] "Folded Mountains and Isostasy," *Bull. Geol. Soc. Amer.*, Vol. XXXVIII (1927), p. 263.

many were not structurally intact at a stage when most of the thrusting had been effected.

A casual approach to the problem might suggest that the maximum force needed in overthrusting would be required for the production of the rupture marked by the fault plane. It would seem, however, that, with even small stress difference at the beginning, compression creep would initiate a fracture, small at first at the source and expanding bit by bit until it emerges at the surface. No greater stress difference may be needed for the development of the sole than for the later slow movement over its surface.

A variety of processes may express a yielding to compression creep. If a great overthrust sheet could be examined along its sole from the surface into the roots at greater depth, it might be expected to show every process from cataclasis to solid flow by recrystallization. Recoverable strain might exist locally beneath a sole, and melting near the roots is not unlikely.

PERIODICITY OF MOUNTAIN FOLDING IN THE THERMAL-CONTRACTION THEORY

One of the many questions involved with the thermal-contraction theory of earth deformation relates to the manner in which the pent-up energy of compression in the crust expends itself. According to Harold Jeffreys,[4] the magnitude of the linear contraction during the geologic record amounts to 5 parts in 800 or 1,000. This suggests from the usual approach that about five or six times in earth history compressive forces would be accumulated to the limit of strength of the crust, and each time a collapse would result in widespread folding and thrusting. In each such revolution the peak of deformation would be expected in an early stage, but some time would be involved with lesser deformation associated with the waning of compressive stress. The time of deformation would be relatively brief, however, when measured with the geologic scale. Evidences from earth history have been interpreted in some quarters as favoring this view of periodicity of contraction and of contemporaneity of folding

[4] *The Earth* (2d ed.; Cambridge: University Press, 1929), pp. 285, 287; *Earthquakes and Mountains* (London: Methuen & Co., 1935), p. 145.

in widely separated areas; but these broad evidences are perhaps more favorable to another concept, namely, that folding is not limited to brief periods but may be an almost continuous process, and is more certainly not confined to the limited number of crises of short duration. The principle of compression creep definitely favors the latter view.

If the earth's commonly assumed crust were incompressible and had finite strength, and if thermal contraction went on to a final collapse, deformation would be instantaneous and catastrophic. The crust, however, is compressible, and if stresses were permitted to accumulate to the commonly calculated limit of strength, the major adjustment would be immediate, though secondary effects might be somewhat drawn out. There appears, however, to be sufficient radial and circumferential range in the chemical and physical properties of earth material to decree that the commonly calculated limit of linear compression would never be approached. Stress difference sufficient to cause a giving-way to compression creep would likely develop in a stage remote from this limit.

Other geological evidences have a bearing on the same problem. For example, it seems probable that magma has been a fairly persistent component of the outer lithosphere, and the presence of magma in any notable quantity would tend to defeat the building-up of stresses sufficient to cause sudden collapse. Again, adjustments marking the most intense deformations in deeper levels are effected through flow by recrystallization, and this kind of flow is usually regarded as implying great slowness. The most intensive deformations accordingly seem to have taken place slowly, so that folding is best viewed as a long-drawn-out process. Evidence that deformation in orogenic belts reaches its peak at the end rather than at the beginning of the disturbance favors the latter view and opposes the concept of brief, critical periods in which the major effect should come first. Indeed, the same evidence conforms to an opinion held by the writer, namely, that the culmination in orogeny is determined by the intrusion of magma. After all, the most imposing feature of the older and better exposed mountain structures is the dominance of forcefully intruded granitic rocks.

SLOW RECOVERY OF THE EARTH FROM ICE-SHEET DEFORMATION

The evidence that wide areas, formerly occupied by ice sheets, are still rising and tilting, thousands of years after the melting of the ice, is commonly accepted as definite confirmation of the concept of a crust overlying a continuous layer of weakness in the earth. The view is held that such late effects cannot be elastic, because of the magnitude of elapsed time, and that they accordingly sustain the isostatic assumption of plastic recovery of balance. The latter assumption, in turn, is based on the evidence of a fairly even distribution of mass around the earth. The writer holds the contrary views that uniformity of mass distribution does not require a weak shell, and that ice-sheet effects may be dominantly elastic.

In the first place, an even distribution of mass is expected from the manner in which the outer lithosphere has been built. The evidences are clear enough: first, that the outermost layer consists mainly of igneous rocks which were born during the geologic record from a succession of intrusive magmas; and, second, that major deformation is typically accompanied by the widespread appearance of these magmas. With magma so dominant in earth processes, conspicuous unevenness of mass distribution would be very surprising. Neither a continuous weak shell nor a persistent magma zone is required by any analysis of gravity measurements.

Equally important doubt faces the concept of the weak shell in the assumption that adjustments following the ice sheets demand plastic flow in the earth. The principle of compression creep contributes notably to this doubt. The deformation of the earth through long time by the weight of an ice sheet involves not only ordinary creep, with a considerable time factor but compression creep as well, and with it a greatly magnified importance of time in creating strain. In discussing ordinary creep, Griggs concluded that, because the rate of elastic flow falls off rapidly under steady stress, the elastic component of creep is "of small importance in geologic applications over long periods."[5] This kind of creep, though permitting some correction to the commonly expressed view that the recovery from elastic

[5] *Op. cit.*, p. 250.

deformation keeps pace with the melting of an ice sheet, does not convey adequately the importance of the time factor in these adjustments toward equilibrium. It happens that when compression creep is involved the linear dimension of the mass assumes importance along with the time factor. To illustrate, two hypothetical instances will be examined. Imagine first an ice sheet formed on an earth with an outer layer, 100 miles thick, consisting of compressible rock lying on an incompressible interior. The ice does not bear down on a detached pillar, where compression would be immediate in all parts and the time factor would embrace only ordinary creep, but on a confined pillar, where outside resistance must be overcome in higher levels before compression can reach lower levels. The time factor accordingly assumes greater importance. In the second hypothetical instance the ice sheet is assumed to rest on an earth so constituted that it suffers only elastic deformation. An approach to elastic equilibrium will consume vastly longer time in this instance than in the former owing to the delay of compression in still deeper layers. The importance of the dimensional factor is thereby indicated. It follows that the time of recovery from strain caused by an ice sheet is related to the length of life of the sheet.

With the knowledge that the Ice age embraced several glacial and interglacial epochs, with ice sheets from various centers and of differing size and duration, a colleague, Dr. Frank Allen, made the interesting suggestion that the present recovery from deformation might be influenced in rate by memories of strain caused by ice sheets preceding the last of the series from the analogy of the so-called "remembering" of earlier deformation by metals.

SUMMARY

An interesting application of compression creep is found in the correlation it provides of the geologic facts of slowness of deformation and magnitude of effects. The evidence, derived on theoretical grounds and demonstrated by rubber sheets, is clear that a small force may accomplish in long time the same effects which would require a greater force in brief time.

The process of compression creep is probably involved in all geological deformations where stress differences require the relative

displacements of large solid masses, since rock has notable compressibility. The movements in glacier ice and in large masses of rock salt are probably no exceptions to this generalization.

Again, the principle permits a clear explanation of how overthrust sheets of great areal extent overcome friction while remaining structurally intact. The same process seems to throw light on the problem of the duration and periodicity of mountain folding; it definitely favors long periods for folding and not a limited number of short periods with long and quiet intervals between.

The assumption that uplift marking present-day recovery from ice sheet deformation implies plastic adjustment in a weak shell appears to be unreasonable in the light of the principle of compression creep, so that one of the main supports of the isostatic weak shell loses value.

A conclusion of some concern to structural geology may be repeated, namely, that intense local deformation may result from small regional differences of stress in masses of great linear dimension. Moreover, these local deformations may, in the course of time, embrace most or all parts of the region to give an erroneous impression that mighty forces were at work.

SWELL AND SWALE PATTERN OF THE MANKATO LOBE OF THE WISCONSIN DRIFT PLAIN IN IOWA

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ABSTRACT

Airplane photographs of the Wisconsin drift plain in Iowa disclose a pattern of light and dark streaks on the ground surface, suggestive of the changing outline of the ice lobe. The streaks are believed to reflect differences in soil composition and texture which probably developed as the result of the slight topographic inequalities of gentle swell and swale. Seasonal fluctuations of the glacial front are thought to have caused the arrangement of swells and swales in the described pattern.

INTRODUCTION

The drift plain of the Mankato lobe of the late Wisconsin glaciation in Iowa is one of slight relief over most of its extent. A very distinctive pattern of the swells and swales in the ground moraine has been discovered from inspection of airplane photographs of the area. This is believed to be essentially one of minor recessional moraines formed as the ice withdrew. The pattern throws light on the direction and rate of retreat of the ice over a considerable part of the area covered by the Mankato lobe in Iowa.

DESCRIPTION

THE MANKATO LOBE

The drift plain of the Mankato lobe covers approximately 10,000 square miles in north-central Iowa (Fig. 1). It extends as far south as Des Moines, a distance of about 130 miles from the Minnesota boundary, and has about the same width along that boundary. It has the shape of a lobe trending somewhat east of south, with a marked re-entrant in the northwest part. The outline is smooth.

Great areas of the drift plain have a swell and swale topography of slight relief, generally of no more than 10 or 15 feet and usually somewhat less. An exaggerated swell and swale rather than a typical knob and kettle topography constitutes the terminal moraine around the southern part of the lobe. The moraine increases in width and

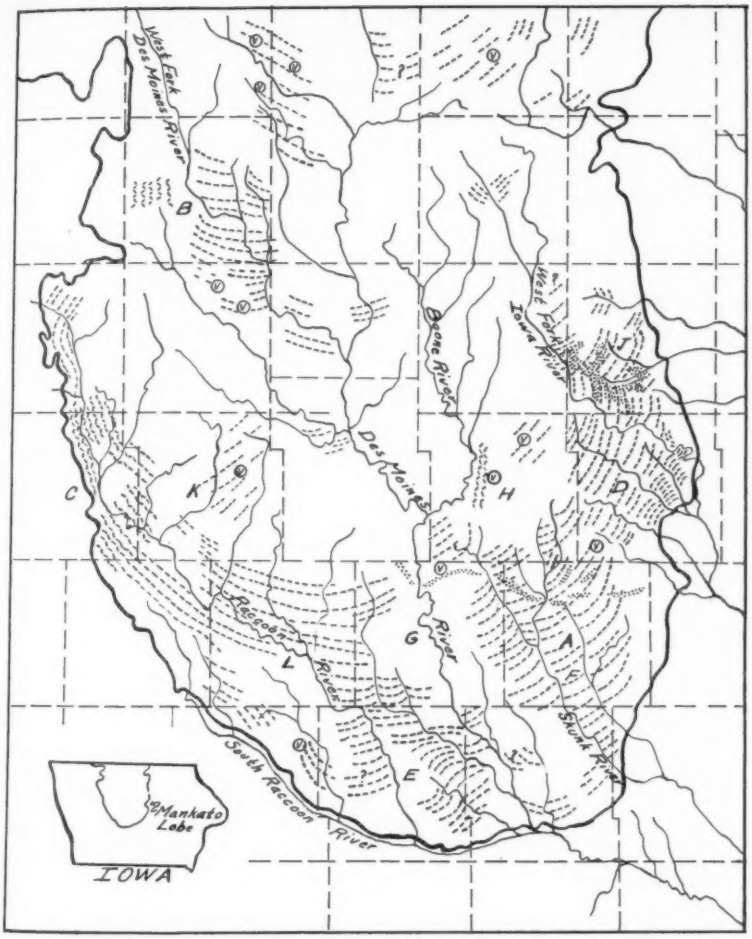

FIG. 1.—Map showing by dashed lines the approximate extent and trends of the swell and swale pattern on the Mankato lobe of the Wisconsin drift plain in Iowa, sketched from photo-index maps of the counties of the area. Letters are referred to in the text. Hilly areas of Story (*A*), Boone (*G*), and Franklin (*J*) counties shown by stippled pattern. Outline of the lobe from publications of the Iowa Geological Survey. Scale 1:1,750,000.

ruggedness toward the north and merges with more hilly ground moraine in the northern counties. Ranges of low hills, usually considered to be recessional moraines, stand out above the level of the drift plain in scattered places in the southern part. Major streams flow in valleys as much as 200 feet below the upland; some of these are sharply incised and have numerous short and deep tributary valleys. Many of the larger valleys are believed to have had a pre-Wisconsin history.

SWELL AND SWALE PATTERN OF THE GROUND MORAINE

The pattern of the ground moraine becomes apparent upon inspection of the photo-index maps of the various counties of the area or of the contact prints of the negatives used in making the photo-index maps.[1] The pattern is formed of narrow, alternating, discontinuous light and dark streaks or patches which give a banded effect (Fig. 2). Individual bands cannot be traced continuously for any great distance, but the pattern as a whole may be continuous for many miles. The bands of the pattern are generally, but not everywhere, concave toward the direction from which the ice advanced. Near the drift margin they tend toward parallelism with the boundary, but with increasing distance from the margin they swing somewhat away from this in a manner which suggests parallelism with the later positions of the ice front. They remind one of the generalized lines of ice sheets drawn on maps to represent their growth and spreading.

Detailed examination of the individual contact prints, on which the scale is larger than on the photo-index maps, shows the banded areas to have a dappled appearance (Fig. 3), an arrangement of the lighter "dapples" along parallel lines producing the banded effect. The dapples are generally elliptical in outline with their longer dimension parallel to the trend of the banding. They range in size from about 70 to 600 feet or more in greatest dimension. The lighter dapples are separated by darker areas of varying definiteness; these darker areas are usually ill-defined and shadowy where crossing the rows of dapples but much more definite between the rows. The darker areas are rather continuous between the rows of dapples, and

[1] The airplane photographs were taken by the Aero Service Corporation, Philadelphia, Pa., for the Agricultural Adjustment Administration, U.S. Dept. of Agriculture, to whom the writer is indebted for the opportunity of studying them.

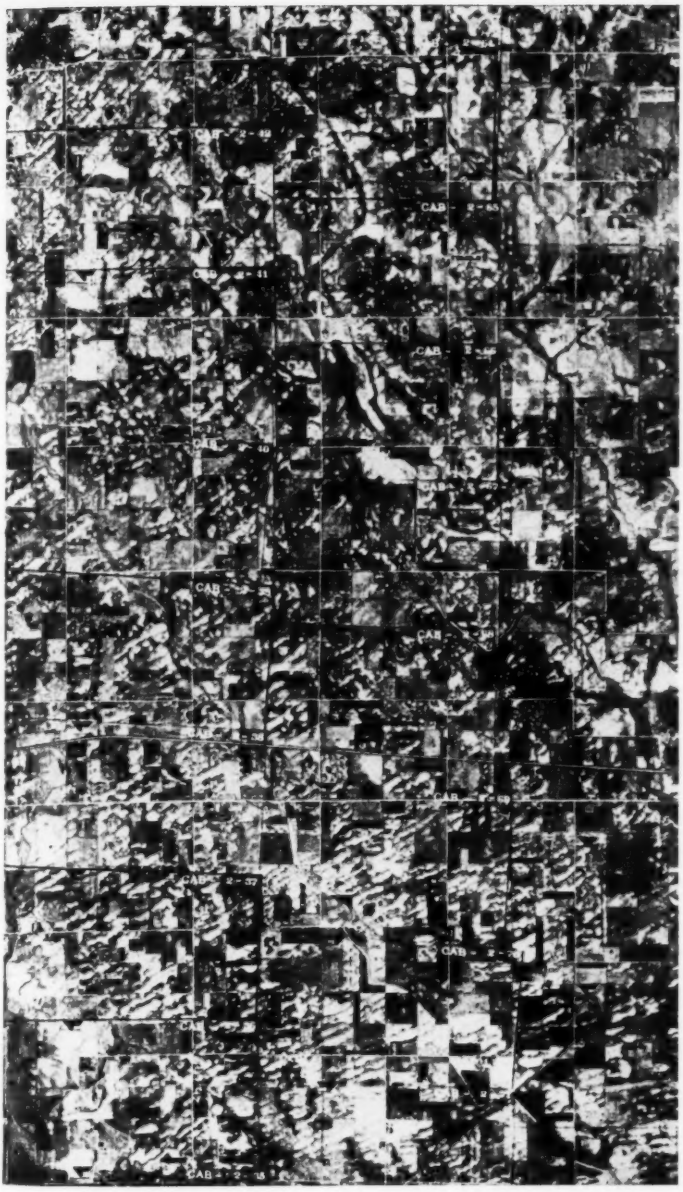

FIG. 2.—Photo-index map of an area in Milford and Grant townships, Story County, Iowa, showing typical pattern and a tendency toward re-entrants along larger drainage lines. Scale 1:84,480. Photograph used with the permission of the Agricultural Adjustment Administration.

minor weak lines of postglacial drainage are in many cases coincident with them. Bands, each consisting of a light and a dark streak, number approximately fifteen to the mile in Story County, toward the end of the lobe.

FIG. 3.—Airplane photograph of an area southeast of Ames, Iowa, showing the pattern as it appears on a scale of 1:20,000. Note drainage lines developing in swales. Photograph used with the permission of the Agricultural Adjustment Administration.

The pattern is missing or only barely discernible in many fields or on many farms in areas which have on the whole a prominent expression of the pattern. This appears to be related to the extent to which artificial drainage has been developed, to the practices which have

been followed in soil cultivation, and to the amount of vegetative cover.

The pattern appears in the photographs over less than half the area of the Wisconsin drift (Fig. 1), being most pronounced in the marginal portion and toward the southern part of the lobe. Almost the whole of some counties, such as Story (*A*),[2] is covered by the pattern. In some parts of the area it is vague, indicated by a *V* on the map. Other areas having only a suggestion of the pattern are indicated by a question mark. The pattern is rather wavy in some places, as in the western part of Palo Alto County (*B*) and the northeastern part of Sac County (*C*). It is usually slightly concave toward the general direction from which the ice advanced, but in a few places, as in eastern Hardin County (*D*) and eastern Dallas County (*E*), the curvature is in the opposite direction. The bands are not continuous across major valleys, but the trend usually continues unbroken. In some cases, as on the divide between Skunk River and West Indian Creek in Story County (*F*), the pattern is scalloped, with re-entrants along the valleys.

DISCUSSION

RELATION OF PATTERN TO TOPOGRAPHY

Inspection of the individual contact prints shows the light parts of the pattern to represent elevations and the dark parts depressions. This is confirmed by observation on the ground surface. The color differences seen on the ground and reproduced in the photographs must be due to differences in soil composition and soil texture; these differences are in turn believed to be a consequence of topographic inequalities which are too slight to show on the standard United States Geological Survey quadrangle maps of the area. The swells presumably have been somewhat eroded since glaciation, particularly by wind action. They have also been more leached and because of better drainage have acquired less humus. The swales, on the other hand, have been somewhat aggraded and, being less well drained, have become higher in humus. The light and dark areas may therefore be the expression of this soil difference. They may also reflect the soil-moisture conditions at the time the photographs were taken.

[2] Letters refer to areas on the map, Fig. 1. In the case of counties these are placed in the approximate center of the county.

The swells, being better drained than the swales, would lose surface moisture more rapidly and appear lighter, whereas the intervening poorly drained swales would retain moisture longer and appear as the dark areas. The pattern might not appear in a photograph taken following a heavy rain. Thus the pattern may possibly be present in some areas where it does not show in the photographs.

MODE OF DEVELOPMENT OF THE PATTERN

It is believed that the relation of the pattern to slight topographic differences is definitely established. Low discontinuous swells alternate with more continuous shallow swales, the latter now in part accentuated by postglacial erosion. Near the margin of the drift the bands are generally parallel to the position occupied by the front of the ice at its maximum extension. They presumably outline successive positions of the ice front as it retreated. The swells are believed to have been initiated through deposition of drift during the summer period of melting. With the ice front oscillating in its retreat, such deposits would be thickened at the margin of the ice as it advanced during the succeeding winter, pushing forward and overriding part of the deposits of the previous summer. The strip not covered by the ice in its readvance would become a line of swales. Neither swells nor swales would be smooth and continuous for any great distance, since the amount of oscillation and deposition along the ice front would not be uniform. Because of this the individual bands as already noted cannot be traced very far on the photographs.

The material of the swales would differ from that of the swells in that it would include more fine outwash. This may contribute to the color differences.

Absence of the pattern over considerable areas in the interior of the drift plain suggests that the ice over those areas was relatively stagnant prior to its disappearance.

RATE OF ICE RETREAT

If the pattern is thus partly seasonal in its development, the spacing of the bands should afford evidence of the rate of ice retreat. The bands, each composed of a light and a dark member, have been counted at places considered representative in Story County (*A*). As already noted, they average about fifteen per mile, showing a rate

of glacial retreat of approximately 1 mile in that number of years. A rather wavy and more compressed pattern, such as is present along the west side of the lobe in Sac County (*C*), implies a slower rate of retreat.

MOVEMENT WITHIN THE ICE

The pattern reveals successive outlines of the shrinking lobe and details of the movement of the ice. The bands are continuous across many drainage lines, and the trend persists unchanged across others where the pattern itself is lacking. The ice front lacked re-entrants in such places. A scalloped front with scallops concave toward the direction from which the ice advanced, developed as in Story (*A*) and Franklin (*J*) counties, shows more rapid retreat along the valleys, believed due to concentration of the glacial runoff. This may be noted in other places. A scalloped front with concavity in the reverse direction, present on the divides of Hardin County (*D*), is much less common and shows that the ice front must have had short salients in these valleys.

The slightly wavy and more compressed pattern noted in Sac County (*C*) is believed to have developed where the retreat was so slow that the seasonal deposits were close together, the advance of one winter coming nearer than usual to the position attained during the advance of the previous winter. Irregularity of movement of the ice as it approached stagnancy is suggested by strips of pattern which are out of line with the rest, as in Calhoun (*K*) and Hamilton (*H*) counties.

The pattern within the lobe shows that the ice withdrew most rapidly from the southeast, so that in time the lobe became more symmetrical and lacked the southeast trend. The southern end presently came to lie in the basin of the Raccoon River and its tributaries in Greene County (*L*), whence it retreated almost directly north up the Des Moines River basin.

BURIED TOPOGRAPHY

An area of hills in northern Story (*A*) and northeastern Boone (*G*) counties has been considered by Beyer to belong to the Gary moraine of the Wisconsin drift sheet.[3] The hills are in belts and photo-indexes

[3] S. W. Beyer, "Geology of Story County," *Iowa Geol. Surv.*, Vol. IX (1899), pp. 160–63.

disclose that the trend of the pattern in crossing them is at variance with the trend of the belts. One such belt has an east-west trend through northern Story County; the pattern crosses it in a direction which ranges from north-south to northeast-southwest. Another belt of northwestern Story County and the adjacent part of Boone County has a southeast trend, but the pattern is approximately northeast-southwest. Smaller belts trend northeastward, and the pattern crosses them at a small angle. The writer has interpreted these belts of hills as pre-Mankato features mantled by later drift and suggested that they represent buried hills of the Iowan moraine.[4] This is believed confirmed by the presence of abundant pre-Mankato loess, a characteristic of the margin of the Iowan drift sheet, in Story and adjacent counties. The pattern is prominent in southwestern Franklin County (*J*), an area of morainic ridges mapped by Williams[5] as part of the Altamont moraine lying within the margin. Here also the pattern crosses the morainal ridges, suggesting that they too represent buried topography. A similar relation has been noted elsewhere on the Wisconsin drift area in Iowa.

SUMMARY

The drift pattern is described, and its development is ascribed to seasonal oscillation of the retreating ice front and to the partial overriding and thickening of material deposited during the season of melting. This pattern reveals the direction of movement within much of the area of the Mankato lobe and the changing outline of the lobe as the ice retreated. Withdrawal was most rapid from the southeast so that the lobe became more symmetrical after the front had retreated a few score miles. Rate of withdrawal was approximately a mile in fifteen years in Story County. Elevated parts of the drift plain, hitherto thought to be recessional moraines of the Mankato lobe, are explained as buried hills, probably of the terminal moraine of an earlier glacier.

[4] C. S. Gwynne, "Motion of the Wisconsin Ice in Story County, Iowa," *Proc. Iowa Acad. Sci.*, Vol. XLVIII (1941), pp. 289–93.

[5] I. A. Williams, "Geology of Hardin County," *Iowa Geol. Surv.*, Vol. XVI (1905), map opposite p. 490.

AN OCCURRENCE OF CONCRETIONS IN THE POTTSVILLE OF GEORGIA[1]

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ABSTRACT

At Hale Gap, Georgia, are found, in the basal Pottsville, unusual epigenetic concretions consisting of ellipsoidal cores, surrounded by increasingly rectangular concentric laminations out to the margins of the joint blocks in which they have developed.

INTRODUCTION

At Hale Gap, Georgia, located in the rim of Sand Mountain, 3 miles northwest of New England, a town located on U.S. Highway 11, is an unusual occurrence of epigenetic concretions of large size. In this region of Georgia, Sand Mountain and Lookout Mountain run in a northeast-southwest direction across the northwest corner of the state. Both are synclinal in structure and are capped by the Pottsville formation, consisting of some 1,600 feet of massive sandstones and conglomerates, with occasional layers of shale, shaly sandstone, coal, and attendant fire clays.

The concretions occur in the basal shale member of the Pottsville, a member not named in Georgia as a separate formation, but which probably corresponds to the Gizzard formation as described by W. A. Nelson[2] in Tennessee. This shale overlies the Pennington formation of the Mississippian system and is persistent throughout the area, ranging from 50 to 70 feet in thickness.

This basal shale member is, for the most part, a yellowish brown to dark brown, fissile, thin-bedded, sandy shale, breaking into fine slivers on exposure, but exhibiting a tendency to weather into rounded projecting masses of a concretionary character. Such concretionary masses are best developed where the shale is of a coarser-grained and sandier type than usual.

[1] By permission of the state geologist of Georgia.

[2] "The Southern Tennessee Coal Field," *Tenn. Geol. Surv. Bull. 33A* (1925), pp. 40–43.

DESCRIPTION OF CONCRETIONS

At the Hale Gap locality the concretions occur pronouncedly in a sandy shale zone, 12 feet thick, and about 25–30 feet above the base of the shale member. Above this zone is a sandy shale of finer grain passing upward into the more typical, fissile shales; below, the shale is also finer grained. The concretionary zone is separated from the beds above and below by sharp bedding planes.

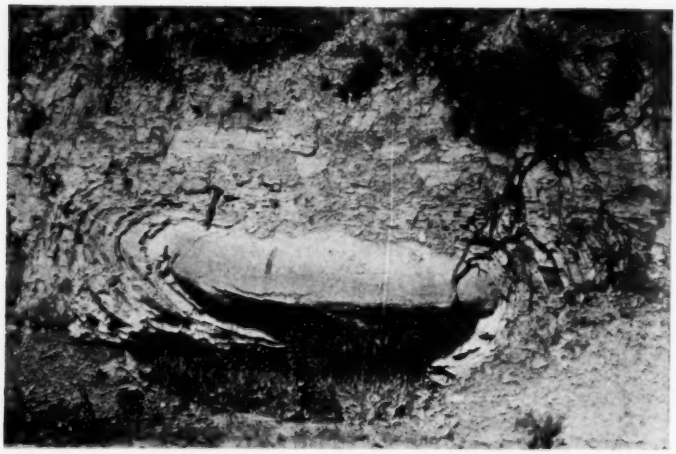

FIG. 1.—Large concretion in shale member of Pottsville

The strata have a slight dip to the northwest and are cut by two sets of joints perpendicular to the bedding planes and trending N. 61° W. and N. 22° E., the former being the more conspicuous. These joints vary from 3 to 15 feet in distance apart and, in combibination with the bedding planes above and below the concretionary zone, define joint blocks of those dimensions. Each joint block (the larger ones including most of the sandy zone, the smaller occurring at intervals vertically through the zone) contains an ellipsoidal concretionary core located in the center of the block. These cores are surrounded by concentric laminas from 1 to 3 inches in thickness which, as they approach the margins of the joint block, become increasingly rectangular. Each joint block shows this independently

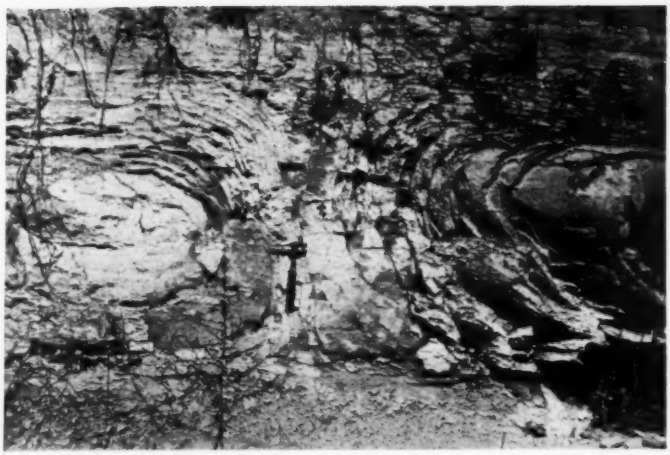

FIG. 2.—Blocks meeting along joint face, showing parts of adjacent concretions and divergent laminations.

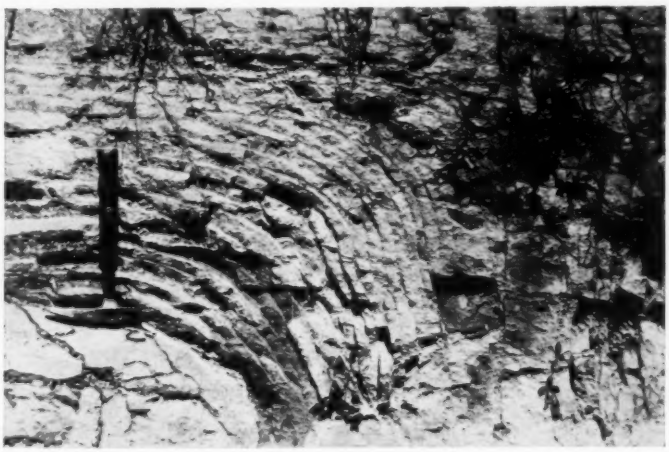

FIG. 3.—Detail of corner of joint block, showing joint face on right and concentric laminations.

of the adjacent blocks, so that along the joint faces these laminas diverge from one another. The laminations are also independent of the bedding planes and occur on all sides of the core.

The cores are very hard and, where broken apart, appear to be homogeneous throughout. They are ellipsoidal in shape, the long diameter being parallel to the bedding planes. The largest core at this locality is 3 by 8 feet, occupying a joint block measuring 8 by 15 feet. Other cores were smaller, ranging downward to about 1 by 3 feet. Where the cores project outward from the road cut, the concentric layers spall off and show an onion-like structure.

In the beds above and below there is a tendency toward the same ellipsoidal form, but it is not so evident in the softer shales. In these layers, too, the rounded forms indicate the passage through them of the bedding planes.

POSSIBLE ORIGIN

The clear influence of the bedding planes and joints upon the shape and character of the concentric laminations indicates that these concretionary cores are epigenetic, but at what stage they were formed in the history of the strata is not clear. It is evident also that the sandier and more permeable zones in the shale member are most susceptible to the formation of such features.

It is suggested that these concretions and laminations were formed while the strata were in a zone of more active ground water than at present; solutions penetrating along the bedding planes and joint faces attacked the enclosed block, dissolving and reprecipitating the contained minerals most actively on the corners and less so at the sides, thus giving rise to increasingly ellipsoidal laminations and concentrating the dissolved minerals in the center of the block to form a hard and homogeneous core.

A DISCUSSION OF THE USE AND MEANING OF THE TERM "LOW AND BALL"

O. F. EVANS
University of Oklahoma

In the very excellent article on "Rip Currents" by Shepard, Emery, and La Fond in the May–June, 1941, issue of the *Journal of Geology* it appears to me that the authors have used the term "ball and low" quite incorrectly, considering both our present knowledge of the origin of such structures and the way in which D. W. Johnson,[1] whom they cite, has explained the use of the term.

As it was originally used by W. H. Wheeler,[2] R. Ray Gresswell,[3] and Vaughn Cornish,[4] the term was applied to a ridge-and-trough structure close to shore which was supposedly formed by the work of the waves. The exact method of formation was not understood at the time. However, it was supposed by Cornish that the ridges and troughs were in some way formed by the shoreward transportation of the sediment by the waves. They were pictured as being somewhat in the nature of large ripple marks and perhaps formed in much the same way.

However, as the term is explained by Johnson and has been used in this country by G. K. Gilbert,[5] I. C. Russell,[6] and others, it means a series of subaqueous ridges and troughs extending for considerable distances approximately parallel to the shore. Such structures have

[1] *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, 1919), pp. 486–89.

[2] *The Seacoast* (London: Longmans, Green & Co., 1902), pp. 41, 118.

[3] "The Geomorphology of the Southwest Lancashire Coast-Line," *Geog. Jour.*, Vol. XC (1937), p. 336.

[4] "On Sea-Beaches and Sand-Banks," *Geog. Jour.*, Vol. XI (1898), p. 637.

[5] "The Topographic Features of Lake Shores," *U.S. Geol. Surv. 5th Ann. Rept.* (1885), p. 111.

[6] "Geological History of Lake Lahontan," *U.S. Geol. Surv. Mono. 11* (1885), pp. 92–93.

also been described along the south shore of the Baltic by Theodor Otto,[7] G. Braun,[8] Sigfried Passarge,[9] and others. E. M. Kindle[10] mentions their presence in Chesapeake Bay; and James R. Kellogg,[11] along the shore of the Gulf of Mexico. They have also been shown repeatedly in aerial photographs.

At the time Johnson wrote his book, the method of formation was not known. Their origin had not been studied except by a few German investigators working along the south side of the Baltic, and it was generally assumed that the ridges were formed by the shoreward action of the waves according to the theories advanced by De Beaumont, Shaler, and Davis in attempting to explain the origin of barrier beaches. The true process by which the "low and ball" is formed was not discovered until I did my work[12] on Lake Michigan in 1939, the results of which were published in 1940. As stated in that paper, they are formed by the work of the plunging breakers, which excavate the trough, or "low," and build up the ridge, or "ball," offshore from it. Since the low is genetically first in the process, I prefer the term "low and ball," as used by Cornish and Johnson, rather than the reversed form.

On page 352 of their article Shepard, Emery, and La Fond apply the term "ball and low" to "the bar and adjacent channel." They describe the channel as being formed by a current which runs nearly parallel to the shore and is a feeder to the rip current. Again, on page 362, they speak of certain subaqueous ridges and troughs as "developed principally as an accompaniment of longshore currents." Thus they apply the term "ball and low" to certain subaqueous troughs and ridges which do not have an origin at all like that de-

[7] "Der Darss und Zingst," *Jahresber. der Geog. Gesell. zu Greifswald*, Vol. XIII (1911–12), pp. 393–403.

[8] "Entwickelungsgeschichtliche Studien an Europäischen Flachlandsküsten und ihrem Dunen," *Veroff. Inst. für Meerskunde u.s.w. 15* (Berlin, 1911), pp. 89–91.

[9] "Physiologische Morphologie," *Mitt. der Geog. Gesell.* (Hamburg, 1912), pp. 195–98.

[10] "Notes on Shallow Water Structures," *Jour. Geol.*, Vol. XLIV (1935), pp. 863–67.

[11] "Notes on Marine Mollusks of Louisiana," *Gulf Biol. Sta. Bull. 3* (1905), p. 38.

[12] Evans, "The Low and Ball of the Eastern Shore of Lake Michigan," *Jour. Geol.*, Vol. XLVIII (1940), pp. 476–511.

scribed for the low and ball by the authors whose work is discussed by Johnson and on which they base their use of the term. It is true that currents sometimes run in the lows and will flow outward over a low place in the ball, but they are merely guided by the lows and balls and are not a cause of their building.

It is my opinion that the troughs and ridges described by Shepard, Emery, and La Fond belong to that group of depressions and elevations nearer inshore than the true lows and balls; and, if they are given a special name at all, it should be one which more definitely links them with the rip currents of which they appear to be a part.

FURTHER DISCUSSION OF THE TERM "LOW AND BALL"

FRANCIS P. SHEPARD
University of Illinois

In the preceding paper by O. F. Evans an interesting point is raised relative to definitions. Previously Evans[1] had investigated the origin of the "ball and low" in portions of the Great Lakes, had presented substantial evidence that these ridges and troughs were the result of wave-plunging, and had inferred that the "low and ball" described by other authors is also the product of plunging waves. Evans then objects to the use made by the writer and his coauthors of "low and ball" in referring to ridges and troughs along the coast near La Jolla, because the latter appear to be primarily the result of currents. This raises a problem concerning which much can be said on both sides. However, since Evans has taken one side, it might be profitable to present points on the other.

The history of geology in the last one hundred years has been one of constantly changing ideas relative to the origin of different features. The term "exfoliation" is a particularly good example of a recent change in opinion. The work of E. Blackwelder,[2] F. E. Matthes,[3] and many others has shown that the old idea of insolation is no longer tenable as an origin for the peeling-off of rock layers. It would seem most unwise to change the name of this physical phenomenon every time some author demonstrates the improbability of a particular hypothesis relative to a particular example of exfoliation. Furthermore, it seems likely now that exfoliation is the result of various processes in different localities. In some cases it appears to be difficult to tell which process has been dominant. The controversy over

[1] "The Low and Ball of the Eastern Shore of Lake Michigan," *Jour. Geol.*, Vol. XLVIII (1940), pp. 476–511.

[2] "Insolation Hypothesis of Rock Weathering," *Amer. Jour. Sci.*, Vol. XXVI (1933), pp. 97–112.

[3] "Geological History of Yosemite Valley," *U.S. Geol. Surv. Prof. Paper 160* (1930), pp. 114–17.

the origin of submarine canyons is another example of the confusion which would result if the authors of the different hypotheses should each adopt a term for the feature according to his concept of the origin. Added to W. M. Davis' term "mock valley,"[4] we might find such terms as "spring seavalley," "tsunamic valley," and "marimud valleys." Such is the confusion to be expected if we apply names to phenomena according to our particular hypothesis of origin.

Relative to the submarine ridge and trough phenomenon observed near La Jolla, it is true that in no case were these features very extensive, so that it could be argued that one should provide a new name for ridges of short length. However, this would lead to confusion, since there are ridges and troughs of highly variable lengths along many coasts, as is so well shown by air views. It would be most difficult to draw a line.

In at least one way the ridge and trough phenomenon near La Jolla appear to simulate closely the "low and ball" described by Evans and others. The thousands of daily and weekly profiles which have been obtained along the Scripps Institution pier[5] show that there are at times as many as three ridges in the zone, extending out approximately a thousand feet from the high-tide shoreline. The development of these outer ridges and the intervening troughs appears to be more related to currents than it is to waves, judging from the comparison of ridge size and character of wave and currents for the period preceding the soundings. These observations make the writer a little hesitant in entirely excluding longshore currents from consideration in the case of the more lengthy ridges and troughs described by Evans. Would it not be better to make daily observations of these features over a considerable period before coming to any final conclusion relative to their origin?

[4] "Submarine Mock Valleys," *Geog. Rev.*, Vol. XXIV (1934), pp. 297–308.

[5] F. P. Shepard and E. C. LaFond, "Sand Movements along the Scripps Institution Pier," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 272–85.

REVIEWS

American Influence in Canadian Mining. By E. S. Moore. Toronto: University of Toronto Press, 1941. Pp. 135. $2.25.

To quote the author, "This study has been made in an effort to determine the major and more direct effects of American influence on mining in Canada and to obtain some conception of the magnitude of this influence."

After a chapter outlining in nine pages the general geological background, the problem which the author has set for himself is attacked regionally under the chapter headings: "The Appalachian Region," "The Canadian Shield," "The Interior Plains Region," and "The Cordilleran Region." The book concludes with chapters on "Capital, Equipment and Technique," "Labor," and "Industry and Trade."

In sketching the geologic background it is pointed out that in the great Canadian Shield area where only small areas were suited for agriculture there would be few important settlements were it not for the mining developments. The blocking of the natural drainage by glaciation furnished abundant sites for the development of cheap electric power for mine operation in a region devoid of coal and oil. Glaciation is also responsible for the lack of placer deposits in a region that has produced nearly three-fourths of Canada's gold—all from lode deposits.

The Appalachian region is considered by provinces. Nova Scotia is the leading coal producer of Canada (80 per cent) and is responsible for about 88 per cent of the gypsum output. H. M. Whitney of Boston played an important part in the consolidation of the leading coal properties into the Dominion Coal Company, now a part of the Canadian-controlled Dominion Steel and Coal Corporation. The principal gypsum producers of the province are American companies or subsidiaries, but Americans have not been prominent in the development of the Nova Scotian gold deposits.

One of the most interesting mines of that part of Quebec that lies in the Appalachian region is the Eustis mine which was discovered in 1865 and which is the oldest *active* mine in Canada. It has been operated continuously under American auspices producing copper and pyrite concentrates. Of Quebec's large asbestos output the United States has taken

annually from 55 to 87 per cent, and American-owned companies have in recent years been responsible for over half of the production.

Among the mining operations of the Canadian Shield province those of Sudbury have been of prime importance to Americans because of their virtual dependence on Canada for nickel supplies. Although the first and most important discoveries in this field were made by Canadians, Americans have from the first played an important financial and technical role in their development. International Nickel Company was organized under New Jersey laws in 1902 and until 1918 refined its nickel-copper matte in New Jersey. In that year, however, as a result of government pressure refining was transferred to Canada. To quote,

> The International Nickel Company of Canada, Limited, was formed on November 30, 1928, by an exchange of stock of the International Nickel Company of New Jersey. In the following year the Mond Nickel Company was merged with the International, which became the only nickel company, with the exception of Falconbridge Nickel Mines, Limited, successfully producing nickel in the Sudbury district. Almost 90 per cent of the world's supply comes from this district of which International produces about 80 per cent.

In December, 1937, 49.9 per cent of the shares of this company were held in Canada and Great Britain, 46.4 per cent in the United States, and 3.7 in other countries. Falconbridge Nickel Mines is dominantly a Canadian company.

In the Cobalt silver-producing district American-controlled companies have been responsible for roughly half of the dividends and bonuses paid. The Nipissing Mining Company was the largest among these.

The Porcupine field produces roughly one-third of the Canadian gold production. "Americans have invested extensively in stocks of Porcupine companies, but they have not exerted as great a controlling influence as in either the Sudbury or the Cobalt fields." American influence at Kirkland Lake has been somewhat more important than at Porcupine.

In 1920 a great boom in mining resulted from the discovery of the rich gold-copper deposits of Noranda in northern Quebec and about a third of the stock of Noranda Mines, Limited, is held in the United States.

In Manitoba American capital has played a dominant role in the operation of the small but rich Mandy copper mine and in the development of the large copper-zinc property at Flin Flon. In Alberta American financial control is said to be responsible for about 95 per cent of the oil production. In British Columbia, Americans were very active in the early development of mining at Rossland and smelting at Trail, and the Sullivan mine at Kimberlie was discovered by an American and its early develop-

ment financed by American interests. This is now the leading single lead-zinc mine in the world.

It has been possible to cite above only a few of the more outstanding instances of American participation in Canadian mining from the large amount of data contained in this volume which will be of great interest and value to all who are interested in the financial, historical, and economic aspects of Canadian mining.

EDSON S. BASTIN

Crater Lake: The Story of Its Origin. By HOWEL WILLIAMS. Berkeley and Los Angeles: University of California Press, 1941. Pp. 101; figs. 9 (including 3 sketch maps); pls. 10. $1.75.

"No thoughtful visitor can stand for long on the edge of this stupendous caldron without wondering how it was formed." To picture to him vividly just how it did form and to let him see and understand how the geologist has read the story by piecing together many bits of telltale evidence has been the aim of this author. He has succeeded surprisingly well.

"Part One: The Story" is a lively narration of the successive happenings whose end product today is beautiful Crater Lake set in impressive surroundings.

"Part Two: The Evidence" is built up by clever dialogue between the ranger-naturalist and members of a small party of Park visitors whom he is conducting to the places of especial significance and interest. This naturalist is even better than the usual "90-day wonder" of the Park Service, and some of his pick-up field class show uncanny perception and logic in their deductions and questions. A geologist, found at work on the problems of Crater Lake, is artfully brought in to help with several of the more difficult points.

The intelligent layman will read this attractive booklet with profitable enjoyment, while many a geologist will admire the skill with which the crucial evidence now available is utilized to give him a clearer understanding of the origin of Crater Lake than he ever had before. According to Williams, 17 cubic miles of the volcano have vanished; the explosions scattered $1\frac{1}{2}$ cubic miles of the old cone and 5 cubic miles of magma as pumice over the surrounding country; 10 cubic miles remain to be explained by caldron subsidence. "Approximately one-tenth of the vanished top of Mount Mazama was blown away in fragments; the remaining nine-tenths collapsed into the underlying reservoir when it was suddenly

drained by eruptions of pumice at the surface and by escape of magma into cracks deep below."

Two beautiful color reproductions of paintings by Paul Rockwood contribute to the artistic merit of the volume.

R. T. C.

Temperature: Its Measure and Control in Science and Industry. By VARIOUS AUTHORS. New York: Reinhold Pub. Corp., 1941. Pp. 1362; illustrated. $11.

In this day of the specialist the strictly theoretical phases of the subject of temperature, as well as the principles of measuring and controlling temperature, must indeed be relegated to the domain of physics. But the broader, more practical aspects of the subject are involved in many other domains of science and of engineering.

This book, which is the record of a symposium held in 1939 under the auspices of the American Institute of Physics, succeeds in co-ordinating the treatment of these broader aspects in several branches of science and engineering. It also comprehensively reviews the fundamental principles of temperature and summarizes the important progress that has been made in the subject in the last twenty years.

The book comprises 126 papers by some of the best authorities in the fields of physics, chemistry, biology, geology, medicine, engineering, and many another profession. Each of the authors gives a picture of the part that temperature plays in his respective profession. The papers are grouped under thirteen main chapter headings.

The first chapter includes a concise discussion of temperature scales in general and provides detailed material incident to numerous basic fixed points. A series of notable papers on precision thermometry, constituting the next chapter, includes valuable practical advice in the development and use of apparatus in both resistance and thermoelectric thermometry.

Of more general interest are the four succeeding chapters, which present illuminating discussions dealing with such varied subjects as "The Measurement of Temperatures in Volcanoes, Fumaroles and Hot Springs"; "Special Geologic Thermometers"; "The Measurement of Stellar Temperatures"; "The Measurement of Upper-Air Temperatures and Their Significance in Air-Mass Analysis." Also presented here are techniques and interpretations of temperature measurements made in biology and medicine. These various considerations give the reader a keener ap-

preciation of the important role that temperature plays in all processes manifested in the universe.

The next few chapters contain detailed descriptions of methods of automatic temperature regulation and recording and special applications of such regulators and recorders in the research laboratory and in the industrial plant. Some of these special applications include the control and measurement of temperature under the microscope, the measurement of flame temperatures, and the measurement of high temperatures in arcs.

Temperature problems in enginering are exemplified by those arising in air-conditioning, by those involved in the control of temperature in massive concrete structures, by those in the metals and ceramic industries, and by those in the oil industries. These, and many similar problems, are discussed at length. For the metals industries the measurement of open-hearth bath temperature is treated in detail. Under "Oil Industries" the important temperature problems incident to thermal prospecting, oil-well drilling, production, and storage of oil are reviewed.

The closing chapters of the book deal with descriptions of optical and radiation pyrometers and with discussions of various metals and alloys useful in thermocouples.

Because of the omnipresence of temperature and temperature problems in either the laboratory or industrial plant, this work should prove invaluable as a reference book for many scientists and engineers.

KENNETH L. COOK

Initiation à la géologie. By J. W. LAVERDIÈRE and L. G. MORIN. Montréal: Editions Fides, 430 est, rue Sherbrooke, 1941. Pp. x+158; figs. 176; pl. 1; Frontispiece. $0.90.

The authors are geology professors at the Université Laval and the Université de Montréal, respectively. Intended for French-Canadian high-school students, this little book makes pleasant reading for any geologist. Practically all the examples are drawn from the province of Quebec or from other localities in Canada. Most of the photographs were taken by the authors themselves in the course of their field work. The treatment is refreshing—the geologist is compared with a historian, his "documents" being minerals, rocks, and formations. Each one of three parts (internal processes, external processes, and glaciation) is logically subdivided in two sections: (*a*) observation and interpretation of facts, and (*b*) application of acquired knowledge to the reconstruction of geologic history. The

language is simple, elegant French (a trifle too poetic, in spots), with remarkably few Canadianisms. One unfortunate feature is the (would-be *moderne*) ugly lettering of the plate and some figures. An alphabetical Index is appended. Profusely illustrated and excellently printed on good paper, with Frontispiece on the cover, the book sells (American publishers, please notice) for ninety cents. This text should provide an ideal preparation in scientific French for our Doctor of Philosophy candidates.

J. D. H. DONNAY

A Miocene Flora from Shantung Province, China. By RALPH W. CHANEY and HSEN HSU HSU. (Pub. 507.) Washington, D.C.: Carnegie Institution, 1940. Pp. vi+147; pls. 57.

Another valuable contribution to the paleontology of China is represented by this work. It deals with a flora from the only known Miocene of China. The flora is made up exclusively of angiosperms, largely dicotyledons, distributed in fifteen orders and thirty families, and a single monocotyledon, *Potamogeton* sp. In contrast to many Middle Tertiary floras of Europe and North America, the Salicales are poorly represented. A marked resemblance is noted with those forests living today at middle altitudes in eastern Asia. The climate is presumed to have been mild and equable.

Owing to the conservative policy of the authors in recognizing specific identity only from fully described and well-illustrated material, comparatively few species of the flora have been recorded elsewhere. Eight species, however, are recognized as identical with those recorded elsewhere in the world. These indicate an Upper Miocene age for the flora. This conclusion is borne out by a study of the mammalian remains from the same horizon.

The illustrations maintain the usual high standard which we have come to expect from the Carnegie Institution. Excellent footnotes, Bibliography, and Index are of help to the student.

ERNEST P. DUBOIS

Geologic Studies in Southwestern Kansas. By H. T. U. SMITH. (University of Kansas, Bulletin 34.) Lawrence, Kan., 1940. Pp. 212; pls. 34; figs. 22.

Admittedly this report raises more questions than it answers, for its avowed purpose is to serve as a foundation for later, more detailed studies.

Fourteen counties in the southwestern corner of Kansas are studied; the broad features of Cenozoic geology and their relations to the natural resources are outlined. The physiography of the area is given a somewhat detailed treatment. A feature of value to future workers in this area is a list of the various sources of geological information which may be consulted.

C. W. STERNBERG

Australia. By GRIFFITH TAYLOR. New York: E. P. Dutton & Co., 1940. Pp. xv+455; figs. 150. $5.00.

This book carries the subtitle, "A Study of Warm Environments and Their Effect on British Settlement," and a good share of the volume is devoted to that phase of the subject. Professor Taylor subscribes to the tenet of the late William Morris Davis that a geographer should explain the geological history and physiographic processes as well as their effects on the peoples who inhabit the region. There is a section which deals with the "natural regions" (analogous to physiographic provinces) with emphasis on the rainfall and vegetation, and another which treats of the discovery, geology, climates, and soils of the continent.

Because there have been no great crustal disturbances of relatively recent time, the topographic expression is subdued. Nevertheless, it is varied and the written explanations of the various features are accompanied by many excellent block diagrams. These are a distinct aid in visualizing the different sections of the continent. There are three main divisions of Australian topography: first, the great western shield, which is about 1,200 feet above the sea; second, the geosyncline, below 1,000 feet and extending from the Gulf of Carpentaria south to the Murray; and third, the eastern highlands. Only about seven or eight horsts are more than 2,000 feet in altitude.

Little in the way of primary ore deposition has occurred since the close of the Paleozoic. Coal beds are well developed and of much importance. The Great Artesian Basin, in the eastern highlands, is the largest artesian basin in the world; Jurassic sediments serve as the aquifers. Finally, soils and their distribution are closely connected with the build of the continent. Having carefully explained the various topographic, geologic, climatic, and other features in the first half of the book, Professor Taylor is in a position to evaluate their effects on the peoples who settled Australia.

C. W. STERNBERG